Arena Ocean Hyway Cluster

HYINFRA

End-user assessment for hydrogen as fuel

Report: A

Project: OHC HyInfra

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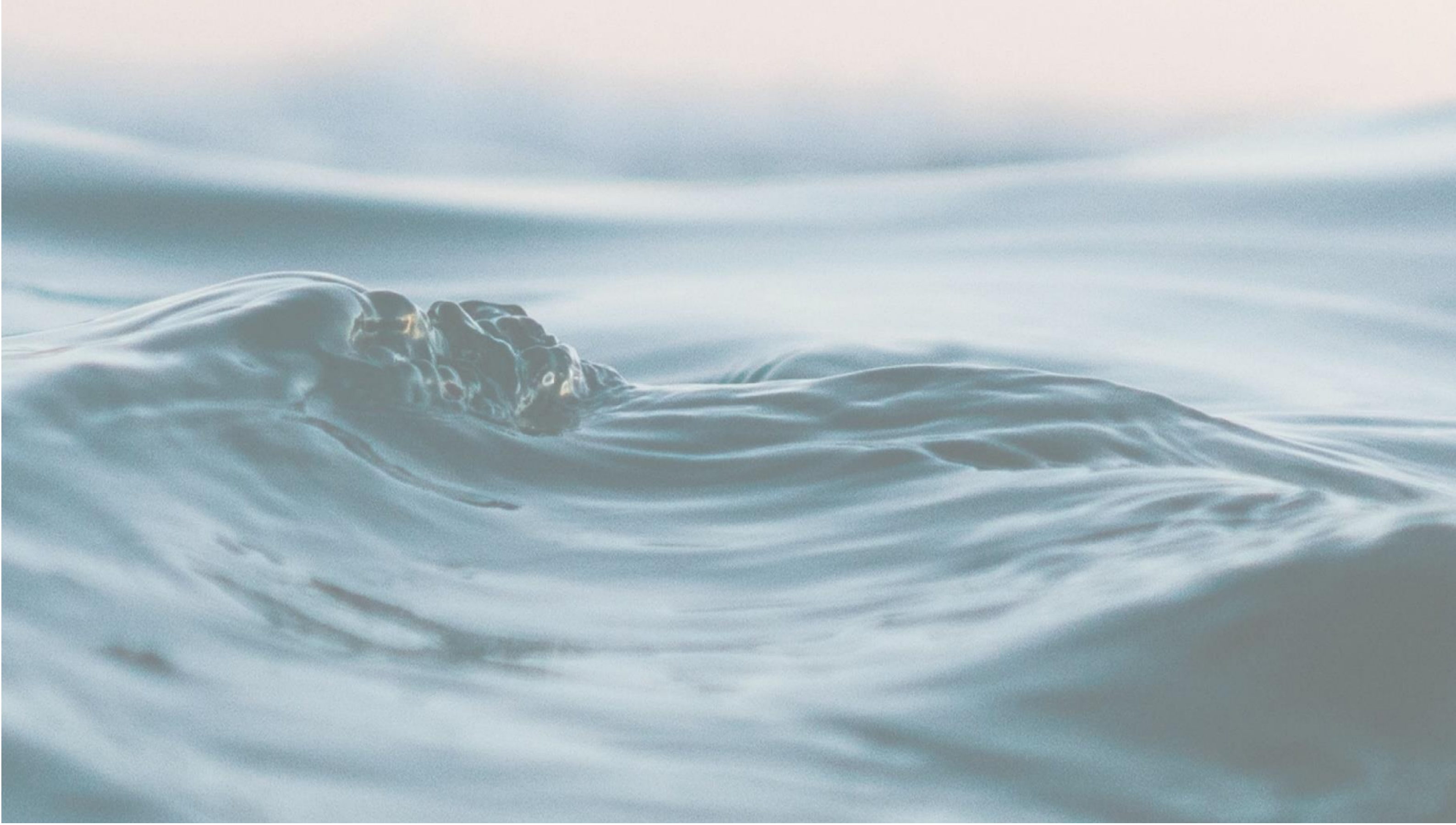

SUMMARY

The current report is part of work package A of the OHC HyInfra project. The aim of the work has been to describe the feasibility of using different hydrogen-based fuels for different vessel types and operations.

It has been found that some fuel options are better suited for certain ship types. However due to varying operational profiles and designs within same ship categories, it is believed that more than one zero carbon fuel will be relevant for the given ship types. The list below gives a rough overview of expected zero carbon fuels, with an indication on primary and secondary energy carriers for the different ships.

Based on the preliminary work as presented in this report, the following general conclusions have been made:

- Compressed hydrogen (CH2) is mainly relevant for ship types and projects where energy storage requirements are relatively low. For ship types with high energy use and several days of operation between bunkering, compressed hydrogen is not considered relevant. On a general basis it is expected that above 1000kg hydrogen use between bunkering operation will be challenging for most vessel types, both due to bunkering challenges and high space claim above deck.

- Liquid hydrogen (LH2) is relevant for the same ship types as compressed hydrogen, however also for vessels with higher energy storage requirements. Due to the higher complexity (and price) of fuel handling systems and the expected high fuel price, liquid hydrogen is not considered the best solution if compressed hydrogen is technical feasible. Holding time, complex bunkering operations and fuel handling issues (e.g. tank sloshing in bad weather) are some of the limiting factors for using liquid hydrogen. LH2 is considered less relevant for vessels with high fuel storage autonomy requirements, high energy use and many weeks between bunkering.

- Liquid ammonia (LNH3) has the highest energy density of the considered fuel types, and the lowest space claim for the tank storage system(s). It is also the only zero carbon fuel where it is expected that internal combustion engines will be applicable, both low speed 2 stroke engines and 4 stroke medium speed engines. For these reasons, LNH3 is considered relevant for most ship types, as there is no obvious limitations with regards to fuel storage autonomy requirements or technology for energy conversion. However due to the toxicity and issues with extreme odor at low concentrations, ammonia is as of today not considered relevant for smaller passenger ships such as domestic ferries.

The below table summarizes the expected zero carbon fuel applicability for different ship types. It should be noted that conclusions may change as technology, price levels and regulations develop. The provided report should therefore only be used for guidance.

Vessel type	Primary zero carbon energy carrier	Secondary zero carbon energy carrier
Cruise vessels	Ammonia	Liquid hydrogen
High speed light crafts	Compressed hydrogen	Liquid hydrogen
Harbour operating vessels	Battery	Compressed hydrogen
Fish farming vessels	Ammonia	Compressed hydrogen
Coastal fishing vessels	Compressed hydrogen	Battery hybrid
Seagoing fishing vessels	Ammonia	Liquid hydrogen
Domestic car ferries	Compressed hydrogen	Liquid hydrogen / ammonia
International car ferries	Ammonia	Liquid hydrogen
General cargo vessels	Ammonia	Liquid hydrogen
PSV and AHTS	Ammonia	Liquid hydrogen
Mobile drilling units (MODU)	Ammonia	None

Arena Ocean Hyway Cluster

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Document History

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1 Introduction

Different vessel types and operating segments have different requirements when it comes to the possible use of hydrogen, or hydrogen carriers, as fuel. This report provides a framework for describing the applicability of the different hydrogen fuel types with respect to vessel size, required operating range and other operational aspects.

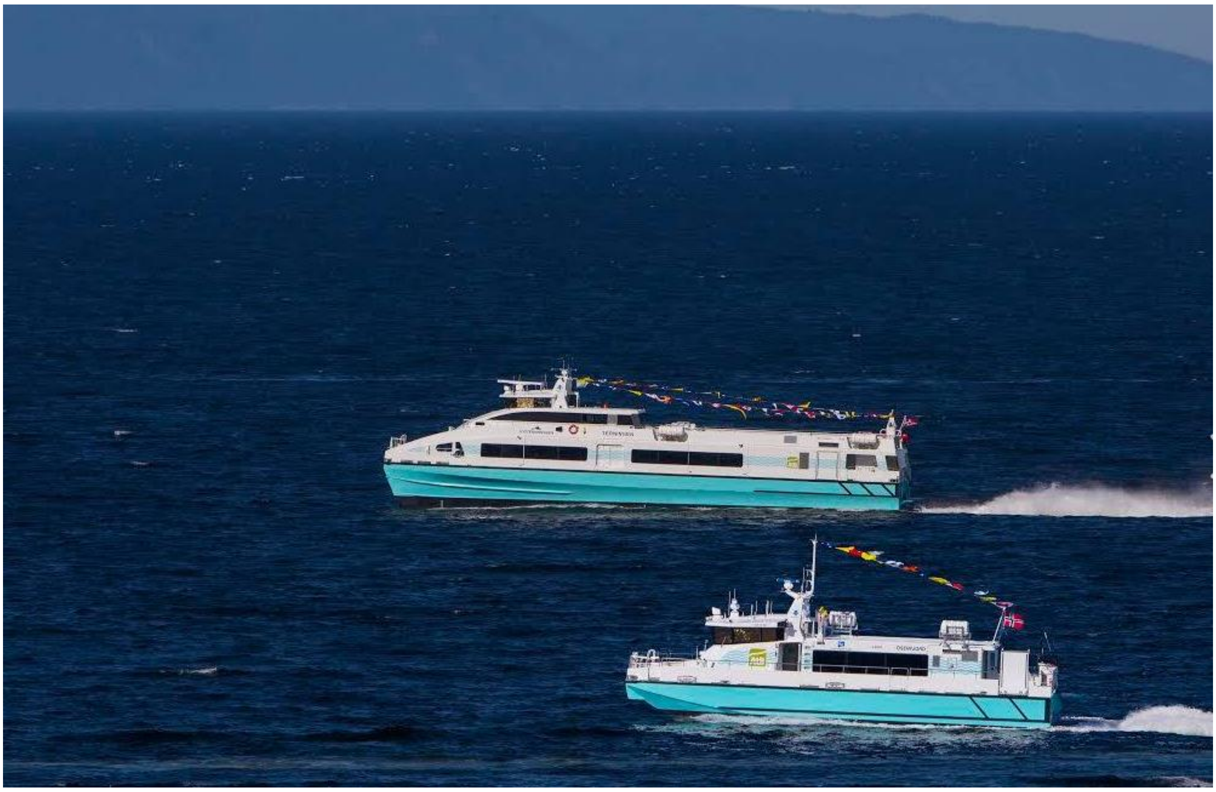


Figure 1*: High speed passenger ferries MS Terningen and Osenfjord. Both vessels delivered by cluster member Brødrene Aa. High speed ferry is a vessel type where future zero carbon energy carriers are open for discussion. Photo by: Jan Olav Storli*

1.1 Objective

The objective of this report is to describe the feasibility of using the different types of hydrogen fuels for different vessel types and operations. The report will describe this from a perspective of energy and power requirements.

1.2 Sources

NHO-report, 2017, "Battery/fuel cell fast ferry", 2017

Oslo Economics, 2016, "Premissanalyser – tiltaksanalyse for utvikling av ferjemarkedet på lang sikt"

Norwegian Maritime Directorate, website with vessel statistics – accessed April 2020

Fiskeridirektoratet, 2019, "Statistikk for akvakultur 2018"

2 Vessel segments to be investigated

2.1 Passenger vessels

The passenger vessel segment is divided into categories as described in the following sub-sections. This report does not consider all sub-categories of vessels, however specific operational requirements will be addressed.

2.1.1 Cruise vessels

Cruise vessels operating in Norwegian waters are diverse, ranging from day cruise vessels for sightseeing inside fjords to the coastal route vessels operating on a fixed all-year schedule and the larger cruise vessels visiting Norwegian waters from abroad. This report divides the segment of cruise vessels into:

- Day cruise vessels, operating within confined waters and short range
- Coastal Route vessels
- Exploration cruise vessels
- Large cruise vessels

With the exception of the Coastal route vessels, cruise operations in Norway are almost exclusively performed between April and October, with the majority of operations in June, July and August. There is, however, a developing market within winter cruises towards Arctic waters, and especially the exploration cruise segment is expected to grow in this direction.

Exploration cruise vessels typically operate out of Norwegian ports and into sub-Arctic and Arctic waters. These vessels have both a demand for long range and for the ability to operate in low or zero emission mode while in vulnerable areas.

2.1.2 High speed light craft

With the exception of one publicly operated combination passenger and cargo vessel in Rogaland, passenger craft in Norway are high speed light craft. The operating speeds vary depending on routes, typically between 20 and 35 knots. The vessels are either passenger-only, or combination passenger and car. There are 91 routes operating HSLCs, both monohulls and catamarans are used. Most routes are in-shore, however quite a few traverse more open coastal waters requiring higher maximum power installed to meet the desired sea margin and safe return to port ability.

The vessels operate on fixed schedules and may in some cases be interchanged on routes depending on traffic and in case of vessels temporarily out of service.

2.2 Work boats

2.2.1 Harbour

Harbour work boats are a diverse type of vessels, ranging from bunkering barges, vessels for maintenance and inspection service, crew transfer vessels and tugs. The vessels are typically small, and operating range is short. Some harbours operate Pilot vessels to support in safe transit, arrival or departure of larger vessels. Pilot vessels are high speed craft with medium range. These vessels are typically designed to service one or a few sites, and operations are carried out locally at the site.

2.2.2 Fish farming

Vessels supporting fish farming operations are typically small catamarans serving as work platforms at site, or high-speed crew transfer vessels. Since most fish farming sites are located close to shore and/or inside fjords the distance travelled by these vessels is short.

In addition, fish farming requires large vessels for carrying out live fish handling operations, such as transfer between sites, medication, counting, de-lice and similar operations. There are also larger vessels carrying and distributing feedstock. These larger vessels operate on longer ranges and between several sites. They do not serve fixed routes. The vessels typically have a large number of tanks, and the hull is utilized to a high extent in order to increase the operability of the vessel. The typical design philosophy is quite close to that of fishing vessels, where utilization of both gross tonnage and deadweight is important for the profitability of the vessel.

There are currently more than 70 fish carriers in operation. The number and size of these vessels are on the increase, the average size being built is above 2500 GT.

There is a move towards establishing larger fish and seaweed farms offshore. This will require larger workboats with longer range and the capability of operating safely in offshore conditions. The workboats will probably be stationed at the farm, and the use of high-speed crew transfer vessels will increase to move people on and off the installation. It is also expected that part of the typical workboat operations will be handled by remote operated vessels and/or autonomous vessels.

2.3 Domestic Car ferries

Car ferries operate both in protected waters in fjords and on routes encountering open coastal waters. The sailing distances vary greatly, from 5-10 minutes up to 4-6 hour crossings of open sea. Most ferries are of the double-ended open deck type, however ferries crossing stretches of open sea usually have enclosed hulls.

Car ferries typically operate at low or medium speeds. The hull design used allows for large unused spaces either below or above deck.

There are 130 public ferry routes in Norway currently, with 250 vessels in operation. The Ampere ferry was the first demonstrator of a fully electric vessel for a fjord crossing, paving the way for the establishment of new contracts that by 2020 will have 80 fully electric vessels in operation. A few of the routes have been converted to LNG-battery hybrid operation, with the prospect of going to LBG as primary fuel.

2.4 General cargo

The general cargo vessels are tankers for liquids and/or gas, chemical carriers, bulk carriers and container vessels. Tanker and bulk carriers typically have high volume hulls and operate at medium to low speeds. Chemical carriers and container vessels have more slender hull forms and operate at relatively higher speeds.

2.5 Fishing vessels

Fishing vessels are generally categorized in size above or below 15 meter hull length. This is due to safety requirements for fishing vessels, with restrictions on area of operation, equipment carried and design criteria for stability.

There are 5978 vessels in operation, the number of vessels has been relatively stable at around 600 vessels since 2010. In recent years there is an increase in larger vessels above 28 metres in length, and a decrease in number of vessels below 11 meters in length.

2.5.1 Coastal fishing

Coastal fishing vessels are typically shorter than 15 m. The restrictions are related to safety requirements both for design and for area of operations. These restrictions typically also have profound implications for both building and operating costs.

Fishing vessels in general have a high utilization of the available hull volume. The restrictions on length have led to even higher utilization of both hull and deck space for vessels below 15 meters in length, which is a challenge for using fuel systems with lower energy densities.

2.5.2 Seagoing vessels

Seagoing vessels are typically over 15 meter hull length. The typical fishing vessel has little available deck space as this is used for storing and handling of fishing gear, and handling of catch. Space below deck is also utilized to a high degree to facilitate cargo carrying capability.

2.6 Platform supply vessels (PSV)

PSV's are vessels that are used in the supply and transfer of goods, equipment and people to offshore installations. They do have dynamic positioning capabilities in various degrees, and are assigned secondary duties related to oil spill recovery, fire fighting etc. The operating profile of a PSV is dominated either by transit speed or by standby operation at a field. When at base the PSV may use onshore power to avoid local emissions.

2.7 Anchor-handling, towing, supply (AHTS) vessels

The vessels in the AHTS segment are mainly used to install and handle mooring equipment for large floating structures. Given their high bollard pull capabilities they operate as tugs when moving installations between different positions and fields. Some AHTS vessels are used in a PSV mode, especially for on-field operations. The operating profile of AHTS are dominated by onboard power consumers (winches) and high thrust/low speed operations.

2.8 Mobile drilling units (MODU)

Mobile drilling units are movable drilling installations used for oil and gas exploration, but also petroleum production, accommodation and heavy lifting. Mobile drilling units include drill ships, semi-submersible drilling rigs and jackup drilling rigs.

Jackup drilling rigs have jackable legs that can be extended to be fixed on the seabed when the rig is drilling and retracted when the rig is moving to a different location.

Semi-submersible drilling rigs are floating structures, usually in the shape of a large, square deck, supported by columns extending down to pontoons that provide the necessary buoyancy. The rigs can vary the operational draft by varying the ballast, and station keeping capability is provided either by mooring, DP, or position mooring, which is a mix of both.

2.9 FUEL STORAGE CAPACITIES AND INSTALLED POWER ON DIFFERENT VESSEL TYPES

In figure 1 storage tank capacities for different vessel types are given, indicating range of fuel tank capacities (blue bars = low, orange bars = high). Even though operating philosophies are expected to change with the introduction of zero emission fuels such as hydrogen, the figure indicates the relative difference in energy storage requirements for various vessels.

Figure 2 below depicts typical range of installed power on various vessel types.

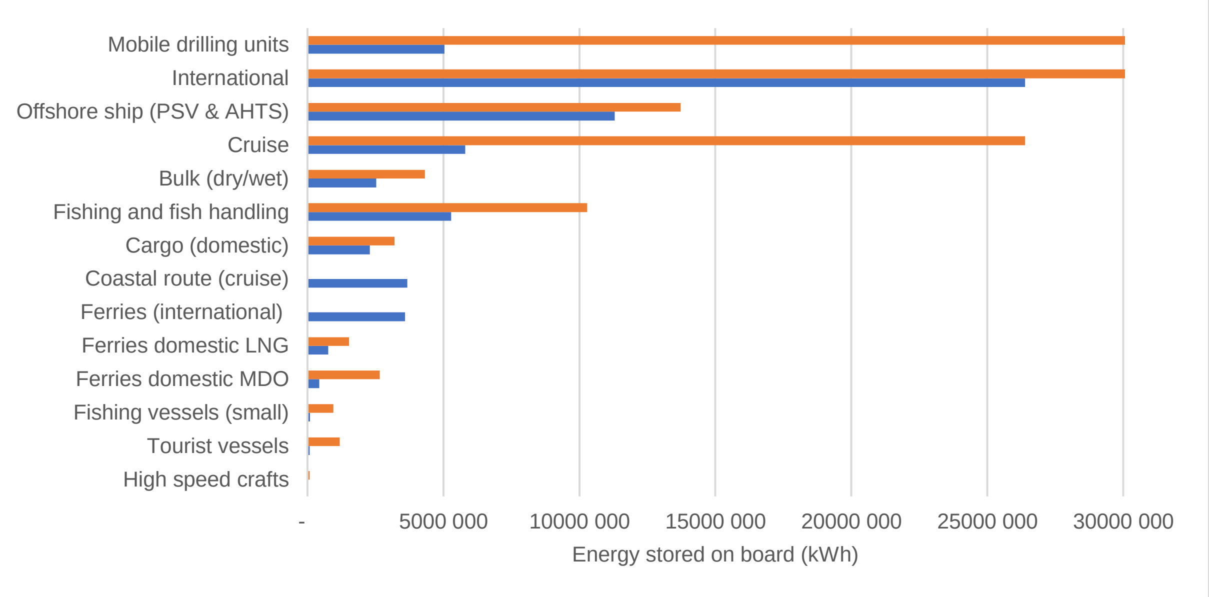


Figure 2: *Fuel storage capacities of various vessel types*

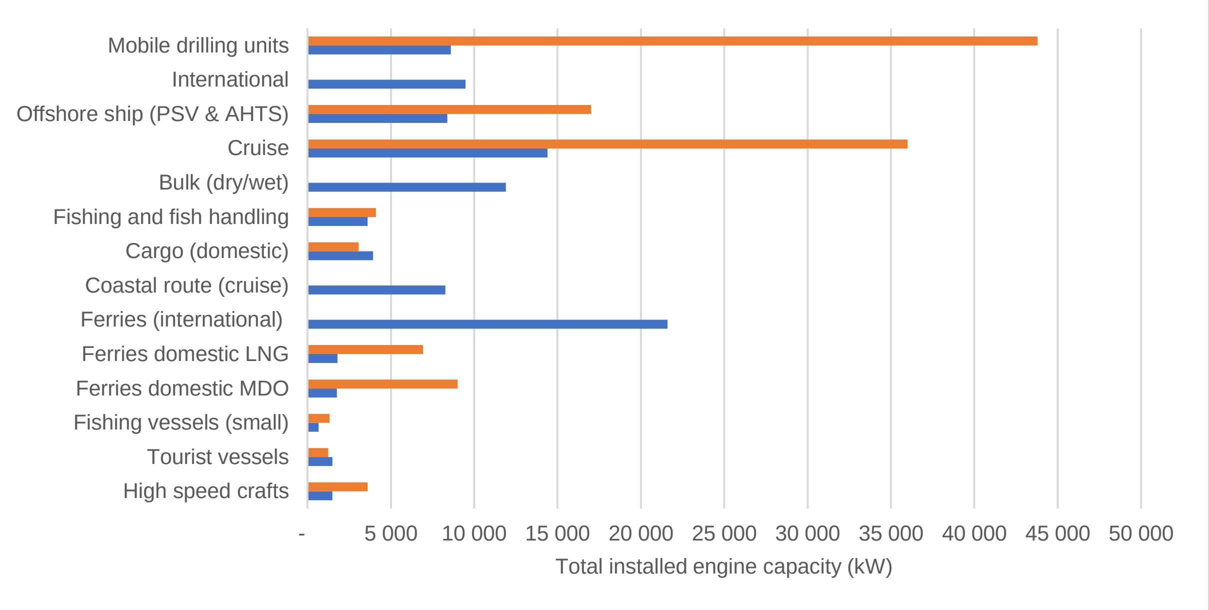


Figure 3*: Installed capacity main propulsion on various vessel types*

3 Hydrogen fuel and fuel handling systems

Hydrogen is the lightest element we know and one of the most abundant both on our planet and in the universe. It is a very reactive element and is never found naturally in its pure form on Earth. Hydrogen gas has extremely low density of 0,082 kg/m^3 at standard temperature and pressure (STP) - 12 times less than air. On the other hand, hydrogen has a very high specific energy density of 120 MJ/kg, which is 2 ½ to 3 times that of conventional fossil fuels.

Hydrogen is invisible, odorless and tasteless. It will burn with a clear, colorless flame with very little radiated heat although in practicality the flame will have slight yellow regions where the air/fuel mixture is rich. Hydrogen is flammable in a mixture with air between 4% and 75% based on volume. The mixture is explosive between 18% and 59%, based on volume.

Hydrogen embrittlement is a problem in some metallic materials, and care should be taken when designing structures that may be exposed to hydrogen.

In order to utilize the high specific energy density of hydrogen it must be converted to a form where it has increased density. This can be done in several ways, either through compression, liquefaction or by utilizing other liquids or solids as 'containers' for the hydrogen.

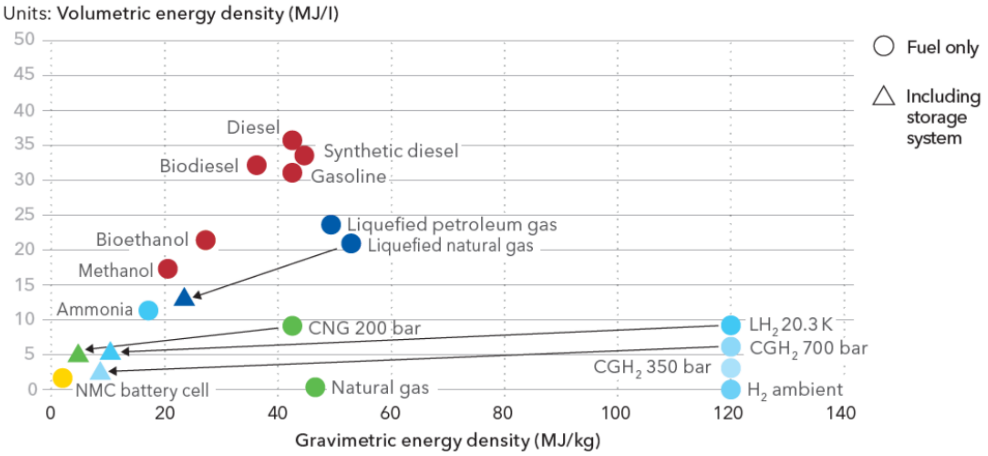


***Figure 4**: Energy density comparison of various fuels. Source: DNV GL*

Hydrogen can be carried in three main forms onboard, either as a compressed gas, in liquefied form or as cryo-compressed gas. Hydrogen can also be carried in the form of Ammonia, NH_3. There are other forms of hydrogen enriched fuels, such as synthetic hydrocarbons where hydrogen gas is combined with CO_2 to form complex hydrocarbon chains and ultimately fuels similar to the fossil fuels we use today. Typical examples are diesel, methane, petroleum gas and methanol. If the CO_2 is captured from air these fuels will be carbon neutral.

Hydrogen will leak from any container, with average leakage rates between 0.5%-1% per 24 hours as typical values. Hydrogen is thus not suited for long term storage.

The following sections describe the primary hydrogen fuels, i.e. hydrogen in gaseous or liquid form, and ammonia.

3.1 Compressed hydrogen

When compressed hydrogen can achieve relatively high densities compared to its liquid form. At 350 bar pressure hydrogen has a density of approximately 23 kg/m^3 which is 280 times its density at STP. By increasing the pressure one can achieve a density of approximately 38 kg/m^3 at 700 bar. In practical terms, storage of large volumes of pressurized hydrogen is done at pressures up to 350 bar due to constraints on pressure vessel weight. Cars and trucks, requiring relatively small volumes of hydrogen, use containers suited for 700 bar.

Compressed hydrogen is seen as relatively safe since any leakage is expected to escape and disperse quickly.

Compressed hydrogen at 350 bar has a energy density of 0,77 kWh/l.

3.2 Liquefied hydrogen

To achieve even higher density hydrogen can be liquefied. The boiling temperature of hydrogen is 20K / -253°C. In its liquid form, hydrogen has a density of close to 72 kg/m^3. The very low temperature of hydrogen is challenging in multiple ways. The need for efficient tank and fuel system insulation is required both to keep the hydrogen from boiling and to avoid severe cooling of structural elements inside a vessel. A leakage will result in flash formation of gaseous hydrogen, at the same time the surrounding atmosphere (air, nitrogen if inert) will solidify due to the extreme low temperature. A leakage will thus form a pool of liquid hydrogen which instantly starts boiling off, and a hydrogen gas cloud with very little initial buoyancy.

Liquid hydrogen has a viscosity 1/100th of water, and will be prone to sloshing in tanks when used in ships. As with LNG systems, sloshing will collapse the pressurizing gas above the liquid and thus stop the outflow of hydrogen from tanks. This is a major issue that must be solved for liquid hydrogen systems.

Liquid hydrogen has a energy density of 2,4 kWh/l.

3.3 Cryo-compressed hydrogen

Hydrogen may be cryo-compressed, meaning that compressed hydrogen is cooled to a temperature between 40K-80K and compressed to 200-300 bar. The density approaches that of 700 bar compressed hydrogen, but is achieved through an increase in system complexity.

3.4 Metal hydrides and LOHC

Hydrogen can be carried in other forms utilizing either a liquid that may be hydrogenated or a metal capable of absorbing hydrogen inside its metallic structure. Both methods of storing hydrogen avoids, to a degree, the problems related to flammability and explosion risk. A liquid organic hydrogen carrier, LOHC, is a liquid with properties similar to biodiesel. Some LOHCs are non-toxic, others non-flammable. Metal hydrides are in general both non-toxic and non-flammable.

There are several drawbacks using either LOHCs or metal hydrides. The weight of the system is significant, with both LOHC and metal hydrides capable of storing 3-8% per weight of hydrogen. This means that storing 1 kg of hydrogen requires 12-35 kg of storage material. These technologies also require substantial amounts of energy for the hydrogenation and de-hydrogenation processes. The systems are not suited for direct feed of fuel to a power system, thus there is still a need for a buffer tank capacity onboard, leading back to the original safety issues.

LOHC has been considered as a useful fuel storage for cruise vessels.

3.5 Fuel systems

All fuel systems for hydrogen require tanks with some pressure handling capability. Liquid hydrogen systems will use gaseous hydrogen over the cryogenic fluid to ensure positive delivery out of the tank at any time. This limits tank systems to cylindrical containers, thus imposing a volumetric penalty in storage spaces.

LNG-systems may use prismatic tanks, thus reducing the volumetric penalty of circular or cylindrical tanks. Depending on development of future common rules and regulations for hydrogen as maritime fuel it may be possible that systems for liquid hydrogen can use prismatic tanks.

4 Ammonia fuel and fuel handling systems

Ammonia (NH_3) is considered as a hydrogen carrier when used as a fuel. Ammonia is used a liquid fuel, either cryogenic or compressed. It has an energy density of 4,3 kWh/l.

Ammonia is toxic and is currently not allowable as fuel for merchant ships due to MARPOL regulations

4.1 Cryogenic Ammonia

Ammonia has a boiling temperature of -33.3°C and can be carried in prismatic or cylindrical insulated tanks. The fuel system is based on carrying liquid ammonia to the end user, thus requiring a cryogenic pump for transfer and/or pressurizing at injection point.

4.2 Compressed ammonia (liquid)

Ammonia can be transported at ambient temperature by compressing it to 10 bar when it is a liquid up to 25°C. This requires pressure vessels and pressure handling capabilities in the fuel system.

5 Comparing zero carbon fuel options

For maritime use liquid hydrogen, compressed hydrogen at 250 bar and liquid ammonia (compressed or cooled) are the zero carbon fuel options considered most relevant. A rough qualitative comparison of ammonia and hydrogen (liquid and compressed) is given below, with focus on parameters relevant for on board fuel handling, bunkering and energy conversion. The comparison is intended to evaluate the technical suitability of the different fuels for use on ships, regardless of technical maturity, safety aspects and regulations. An underlying assumption is thereby that these matters will be solved in existing and future projects. CAPEX and OPEX for the different fuel options are also excluded from the comparison due to uncertainty related to future cost developments.

As indicated in the table below, there are major differences in fuel properties for the relevant zero carbon fuels.

Description	Compressed hydrogen (CH2)	Liquid hydrogen (LH2)	Liquid ammonia (LNH3)
Volumetric energy density	(red)	(yellow)	(yellow-green)
Complexity on board storage and handling	(yellow)	(red)	(red-yellow)
Complexity bunkering procedures	(yellow-green)	(red)	(red-yellow)
Bunkering rate	(yellow)	(yellow-green)	(yellow-green)
Limitations bunkering volumes	(red-yellow)	(yellow-green)	(green)
Energy conversion efficiency	(green)	(green)	(yellow-green)
Scalability	(red-yellow)	(yellow)	(yellow-green)

5.1 Energy density

One of the most important property of any maritime fuel, is the volumetric energy density and subsequent space claim. Compressed hydrogen has a relatively low energy density in its compressed gaseous form and will with current available technology be stored in several compressed hydrogen cylinders, leading to additional space claim.

The volumetric energy density of liquid hydrogen at STP is approx. 4 times higher compared to that of compressed hydrogen. Liquid hydrogen can be stored in type C vacuum insulated tanks custom made for the required storage demand, thus requiring less additional space compared to compressed hydrogen.

Of the considered fuel types, ammonia has the highest fuel energy density and the expected lowest tank system space claim.

Based on the above, compressed hydrogen is expected to be less relevant as a primary fuel for vessels with high energy storage requirements (e.g. international shipping). Ammonia is considered most suitable for vessel types with high energy storage requirements / fuel storage autonomy, where bunkering frequency is low.

5.2 On board storage complexity

The complexity of on-board storage and handling is for compressed hydrogen regarded less complex compared to ammonia and liquid hydrogen. This is because compressed hydrogen will be stored and used in gas phase. It is expected that compressed hydrogen tanks will be located above deck in open air, leading to less safety risks related to leakages (compared to liquid hydrogen and ammonia).

For liquid hydrogen storage and handling is considered very challenging, both with regards to processing and safety barriers. One of the main challenges with liquid hydrogen is the low temperature and the consequent need of complex storage tanks that can keep the fuel in liquid state. Other challenges with liquid hydrogen is fuel processing (evaporation and pressure regulation) and systems to avoid unacceptable pressure loss in the event of tank sloshing.

Ammonia storage systems are expected to be less complex compared to liquid hydrogen, however due to toxicity, sophisticated safety barriers are expected. Also fuel processing (evaporating and pressure build up systems) will be needed prior to energy converter (engine). From a technical point of view ammonia fuel systems are similar to existing commercial LPG fuel systems.

5.3 Bunkering complexity

Because of the boiling temperature (around -253°C at 1bara) of liquid hydrogen, bunkering procedures are expected to be extremely complex. Safety zones, bunkering line inerting and purging, boil off handling, pre-cooling of piping and air condensation on bunkering equipment are some of the challenges that must be handled.

Bunkering of compressed hydrogen is expected to be less complex since bunkering will take place with hydrogen at ambient temperature and fuel is only in gas phase.

Ammonia bunkering is expected to be less complex, however safety challenges and complex procedures are expected also for this fuel. For ammonia, safety zones are expected to be significant and high standards with regards to safety barriers are expected due to toxicity.

5.4 Bunkering rate and volumes

Bunkering rate and limitations on volumes are expected to limit the applicability of compressed hydrogen in ships with high required energy storage capacities. Fuel transfer rates (kg/h or MJ/h) are for compressed gaseous hydrogen relatively low compared to liquid fuels. The transfer rate can be increased by adding bunkering connections; however, this will increase the complexity of systems and bunkering procedures. Another issue with bunkering of compressed hydrogen, is the need of large volumes of hydrogen on the bunkering source (land or ship if ship-ship transfer). Today's bunkering procedures involve cascade filling which requires large volumes at the source (up to 2x on board tank volume) in order to fill on board tanks.

For liquid hydrogen transfer rates are expected to be high compared to compressed hydrogen. Transfer can be done by pressure build up in tanks on bunkering source or by using cryogenic pumps. With regards to volumes, large bunkering volumes will be expensive, however possible if ship-ship transfer or if having storage tanks on land. If distribution by truck, the volume delivered will be limited by the capacity of LH2 container/tank on truck.

Ammonia is a commercially traded commodity, with several million tons transported by sea annually. There is thus substantial knowledge on transfer operations that will be applicable for bunkering.

6 APPLICABILITY OF HYDROGEN OR AMMONIA AS FUEL

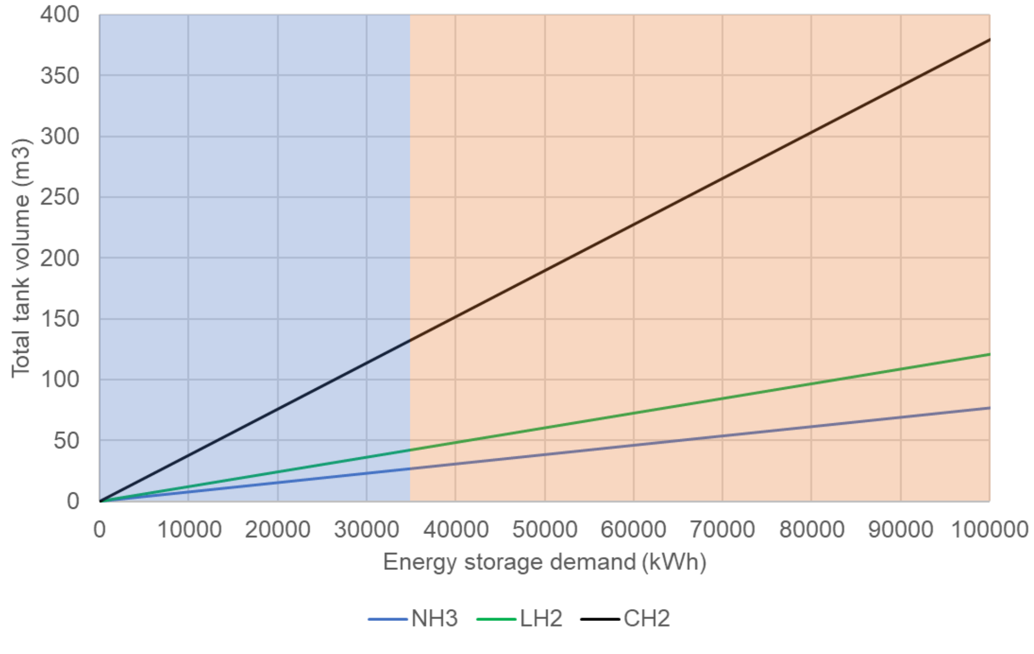
This chapter looks at the different vessel types and gives a short account for the applicability of hydrogen and ammonia as fuel. It does not consider safety aspects or environmental concerns regarding potential accident hazard and spills.

6.1 GENERAL CONSIDERATIONS

When comparing liquid hydrogen, compressed hydrogen at 250bar and liquid ammonia, the most obvious difference is the fuel storage system energy density. The figure below indicates theoretical tank volumes for the different fuel types as a function of energy storage demand (energy use between bunkering). The required storage volume of compressed hydrogen at 250bar exceeds 100m3 below 30 000 kWh (<1000kg). With current available technology, storing 100m^3 of CH2 would imply 20-40 compressed hydrogen tanks with manifolds and H2 processing equipment installed above deck. As the latter is deemed challenging for most ship types, compressed hydrogen is considered a less likely solution for ships with more than 35.000 kWh fuel demand between bunkering operations.

For higher energy storage demands (orange area in below figure), liquid hydrogen or ammonia is considered more suitable. As energy densities are similar, other aspects are more relevant when comparing liquid hydrogen and liquid ammonia.

One of the main drawbacks with liquid hydrogen is the low boiling temperature, and the subsequent challenge with boil off and limited holding time. Maximum holding time of 2-3 weeks is expected, however depending on tank design and hydrogen consumption. For ships with high required fuel storage autonomy, limited holding time is expected to exclude using liquid hydrogen as a zero-emission fuel for many vessel types. Liquid ammonia is thereby considered more suitable for offshore ships, drilling rigs and in general ships with limited possibility of frequent bunkering.



6.2 CRUISE VESSELS

Cruise vessels generally have high power and energy demands both for propulsion and for accommodating passenger needs. The cruise industry has been developing ever larger ships, with the largest now having 6680 passengers and 2200 crew (Symphony of the Seas, RCCL). With the growing focus on environmental issues, and climate issues in particular, the industry has been moving towards the exploration cruise segment, where smaller ships are used. The typical capacity of these vessels range from 600 to 1200 passengers.

Utilization of wind through rigid wingsails or Flettner rotors are being explored as means to reduce the capacity of installed power systems. For the hotel and accommodation systems are being develop for increasing the utilization of heat, and also heat storage facilities are being used.

Cruise vessels are generally designed to accommodate passengers above the water line, thus providing relatively ample space in the hull for fuel tanks and energy systems. This provides large volumes for carrying fuel.

Most cruise vessels operating in Norway calls several ports along the coast. This provides opportunity for using hydrogen or ammonia as fuel, if these fuels are available at Norwegian ports.

The announcement of requirements for zero emission operations in Norwegian heritage fjords, and several ports, may induce some cruise operators to install zero emission power systems for shorter sailing distances. This may also be used as a solution for exploration cruise vessels, enabling zero emission operation in environmentally sensitive areas while utilizing low emission fuels in open seas.

Cruise vessel designs typically allow for increased utilization of hull volumes below deck for fuel and power systems. Some vessels may have the ability to carry fuel tanks above deck, but this could negatively impact stability since available open air decks are usually high above the water line.

6.3 High speed light craft

Existing vessels have a fuel carrying capability allowing them to operate a full day with refueling happening overnight. Since both hydrogen and ammonia have substantially less energy density than marine diesel oil, the vessels will be expected to perform fueling operations more often, either at every end of the route or at every roundtrip. The vessels may carry fuel tanks on open deck or below deck if regulations allow. Compressed hydrogen will provide sufficient capacity for such operations on all routes in Norway, however operational considerations may favour the use of liquid hydrogen to enable increased range and fewer bunkering operations per day.

6.4 Harbour operating vessels

The work boats in harbours are more suited for fully electric operations since they will be operating close to a charging point. The utilization of energy is much higher in a purely electric system, and thus it is not expected that hydrogen will be a suitable option for such vessels.

6.5 Fish farming vessels

Smaller work boats and crew transfer vessels are expected to be battery operated, due to the short distances travelled and availability of charging points.

The larger fish carriers have higher power and energy demands. Since these vessels have highly utilized hills and the deck space is needed for equipment it will be necessary to use a fuel with as high energy density as possible. These vessels thus lend themselves to the use of ammonia as fuel. Due to the nature of fish handling operations onboard these vessels may be most suited for cryogenic ammonia, since the fuel can be used for cooling purposes onboard.

The new feedstock vessels being built are larger vessels, capable of supporting several sites. These vessels may accommodate compressed hydrogen systems with tanks mounted above deck.

With fish farms moving offshore the vessels will need increased bad weather handling capabilities. This often means higher power requirements. Due to the expected issues with sloshing in liquid hydrogen tanks it is assumed that ammonia will be the more suitable fuel for such operations.

6.6 Domestic Car ferries

Most routes in Norway are or will be operated by all-electric ferries within the next 2-5 years. There are a few longer routes, or routes operating in open seas, that currently may be considered for operating with hydrogen or ammonia. The vessels in use on these routes typically have much available space both below and above deck. The use of compressed hydrogen on these routes will probably require frequent refueling, while using ammonia may enable daytime operations with overnight refueling.

6.7 General cargo vessels

These vessels, while diverse both in operations and sailing distances, may be divided into two groups.

Tankers and bulkers generally have voluminous hulls with the capacity of carrying relatively large volumes of fuel without affecting cargo capacities. Most of these vessels may also accommodate substantial tank volumes above deck. These vessels can benefit from carrying liquid fuels to increase range, but they might opt for the relatively low cost compressed hydrogen systems due to the financial nature of this trade.

Container vessels and chemical carriers with slender hulls operate at higher speeds and have less available space both below and above deck. These vessels will require liquid fuels with high energy density due to sailing distances and power requirements. The use of ammonia as fuel is probably the most attractive option for these vessels.

6.8 Coastal fishing vessels

The smaller (<15 meters) fishing vessels have operational profiles where they go at speed to the fishing areas, spend several hours at relatively low power while fishing or handling the fishing gear (pods, nets, etc.) and then return to port at speed to deliver the catch as fresh as possible. The fishing vessel "Karoline" is of this type, fitted with a battery that allows ½ transit to the field and ½ hour transit back, while allowing up to 8 hours operating at the fishing site. When more range is needed "Karoline" has a small diesel generator to charge the battery.

With the development of higher capacity batteries it is expected that these fishing vessels may be electrified in the same way as "Karoline" but with longer range. An option may be to fit such a vessel with a car type fuel cell system charging the batteries to increase range further. This will then be compressed hydrogen at 700 bar. The use of ammonia or liquid hydrogen is not considered for this type of vessel since safety requirements may be prohibitive for the type of operation where the fishermen also act as engineers.

6.9 Seagoing fishing vessels

These vessels have dedicated engine room crew and may benefit from liquid fuels with high energy densities. The considerations are similar to that for fish carriers, given that the design philosophy is similar. High utilization of hull space and limited available deck space, while needing high range to reach distant fishing areas, lends itself towards using ammonia as fuel. The use of cryogenic liquid ammonia will enable utilization of the fuel for cooling purposes onboard.

6.10 PSV and AHTS

These vessels have high power demands, and requirements to standby ability offshore. This means the vessels will benefit from having the most energy stored onboard as possible, since they may also be asked to assist in SAR operations. Ammonia would thus be the fuel of choice for these vessels.

6.11 Mobile drilling units (MODU)

Mobile drilling units in general have high fuel storage requirements and high-power requirements. Bunkering operations will take place offshore from ship to rig, in challenging weather conditions. In general hydrogen is not considered relevant as a fuel for main propulsion for mobile drilling units due to low energy densities, complex storage systems, explosion hazards and bunkering procedures. If any, ammonia is considered the only relevant zero carbon alternative fuel for MODU.

6.12 Overview – Ship types and expected zero carbon fuels

Table 1 summarizes the expected zero carbon fuels for different vessel categories.

Primary energy carriers are the anticipated fuels for the different ship types, based on operational constraints, power requirements and fuel autonomy/energy storage requirements. However, there are large variations in operational patterns and requirements for ships within the same category. For this reason, it is considered likely that more than one zero carbon fuel option will be relevant (secondary zero carbon energy carriers are relevant for some vessels).

***Table 1**: Overview ship types and relevant future zero carbon fuels*

Vessel type	Primary zero carbon energy carrier	Secondary zero carbon energy carrier
Cruise vessels	Ammonia	Liquid hydrogen
High speed light crafts	Compressed hydrogen	Liquid hydrogen
Harbour operating vessels	Battery	Compressed hydrogen
Fish farming vessels	Ammonia	Compressed hydrogen
Coastal fishing vessels	Compressed hydrogen	Liquid hydrogen
Seagoing fishing vessels	Ammonia	Liquid hydrogen
Domestic car ferries	Compressed hydrogen	Liquid hydrogen / ammonia
International car ferries	Ammonia	Liquid hydrogen
General cargo vessels	Ammonia	Liquid hydrogen
PSV and AHTS	Ammonia	
Mobile drilling units (MODU)	Ammonia	