



RH₂INE Kickstart Study

Scenario Building

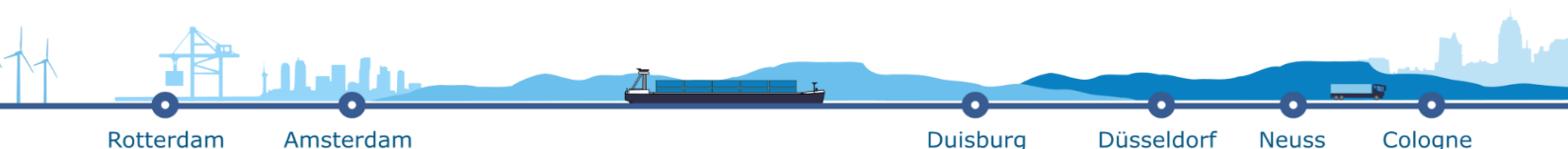
Sub-study Hydrogen Containment Systems



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Rhine Hydrogen Integration

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SuAc 1.1a Hydrogen Containment Systems

RH2INE Consortium

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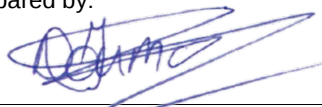
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Objective: this report provides an overview of hydrogen storage methods and containment systems including the relevant physical parameters (such as pressure, temperature, state of aggregation etc.). Specific focus is given to the differences in energy densities and the disadvantages and advantages per storage method/system. The report also contains an introductory chapter on the various fuels that can be applied in IWT and the relevant criteria & conditions that make a fuel suitable for IWT.

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ABREVIATIONS

ADN	European agreement concerning international carriage of dangerous goods by inland waterways
ARA	Amsterdam, Rotterdam, Antwerp
CAPEX	Capital Expenditure
CH ₃ OH	Methanol
CO ₂	Carbon Dioxide
ETS	European Emissions Trading System
GHG	Greenhouse Gas
H0-DBT	Dibenzyltoluene
H18-DBT	Perhydro-dibenzyltoluene
HVO	Hydrogen vegetable oil
IMO	International Marine Organization
IWT	Inland Waterway Transport
LNG	Liquid Natural gas
LOHC	Liquid Organic Hydrogen Carrier
NaBH ₄	Sodium borohydride
NO _x	Nitrogen oxides
MGO	Marine Gas Oil
NRMM	Non-Road Mobile Machinery Directive of the EU
OPEX	Operating Expenditure (here used incl. fuel)
PEM	Proton-Exchange Membrane fuel cell
PoR	Port of Rotterdam
R&D	Research and Development
RH2INE	Rhine Hydrogen Integration Network of Excellence
SCR	Selective Catalytic Reduction
STS	Ship-To-Ship

EXECUTIVE SUMMARY

Introduction

Efficient hydrogen storage for transport and propulsion on board of inland navigation vessels is an important enabling factor for use of hydrogen as a fuel in the inland waterway transport (IWT). Hydrogen has the highest energy per mass of any fuel, however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density.

The Rhine Hydrogen Integration Network of Excellence (RH2INE) is an international programme and consists of public and private parties. Its global aim is to implement hydrogen as a fuel in IWT. This report is the result of “sub-activity 1.1a: Identification of hydrogen containment systems for transport and propulsion on board of inland navigational vessels” of the tender “sub-study 1a: Safety framework conditions” issued by the Port of Rotterdam Authority (PoR) on behalf of the RH2INE consortium.

Objective

This sub-activity has the objective to provide an overview of hydrogen storage methods and containment systems including the relevant physical parameters (such as pressure, temperature, state of aggregation etc.). Specific focus is given to the differences in energy densities and the disadvantages and advantages per storage method/system.

The report also contains an introduction (chapter 2) to the various fuels that can be applied for IWT and the criteria & conditions that make a fuel suitable for IWT.

Approach

As a starting point a literature review was conducted to identify the possible hydrogen storage methods and containment systems. Information about the working principle, physical parameters, state of development and the advantages and disadvantages of the hydrogen containment systems was found and used to construct the basis of this report. The information was supplemented by reviewing DNV reports and projects, an internal DNV expert workshop, a review on design standards and technical specifications and by conducting interviews with technology manufacturers and project initiators of hydrogen pilot vessels.

Conclusion

Containment systems are identified for each storage method and storage conditions (pressure, temperature, physical state and storage density). An overview is provided in the table on the next page.

Table 1: Overview of hydrogen storage methods, containment systems and physical parameters for use in IWT.

Storage method	Containment system	Pressure	Temperature	State of aggregation
<u>Physical-based</u>				
Pressurized	<u>Fixed</u> : Pressure cylinders/tubes (type I,II,III & IV) <u>Swappable</u> : type I-IV cylinders/tubes in cylinder racks, or 20/40 ft ISO tube- or cylindercontainers.	200-500 bar	Ambient	Gas
Liquid	<u>Fixed</u> : Super insulated tanks (IMO type C) <u>Swappable (possibly¹)</u> : Super insulated ISO tank-containers	Atmospheric to 5 barg ²	-245 to -250 °C	Liquid
<u>Material-based</u>				
Sodium borohydride (NaBH₄)	Crystal: Storage similar to salt (plastic containers) Liquid: Plastic containers, IBC tanks, storage for corrosive liquids	Atmospheric	Ambient	Solid (crystal) Liquid (dissolved in water)
Ammonia	1. Insulated tanks	1. Atmospheric	1. -34°C	1. Liquid
	2. Insulated pressure tanks	2. 10-30 bar	2. Ambient	2. Gas
LOHC	Tanks similar to diesel tanks; ISO tank-containers, large (tailored) tanks	Atmospheric	Ambient	Liquid
Methanol	1. Tanks similar to diesel tanks; ISO tank-containers, fixed carbon steel tanks	1. Atmospheric	1. Ambient	1. Liquid
	2. CO ₂ tanks	2. 12-25 bar	2. -35 °C to -15 °C	2. Liquid

Pressurized hydrogen

Pressurized hydrogen storage is currently furthest developed for mobile applications (inland shipping) and is the most applied method in current hydrogen vessel projects. The technical maturity and availability of pressurized hydrogen are clear advantages over other storage methods. The required weight of the containment system, the relatively low volumetric energy density and therefore the space required to store sizable amounts of hydrogen on-board inland navigation vessels are however disadvantages.

Both fixed and swappable systems could be applied in the coming years at storage pressures of 200-500 bar. For the application of fixed systems further analysis is necessary into the bunkering scenarios to assess the bunkering rate as slow bunkering rates could be a disadvantage. Swappable systems can be found in containerized solutions (20/40 ft. ISO containers) or cylinder racks. Swappable systems could be pre-filled, omitting potential delays of bunkering rates, and can be exchanged at a container terminal.

Liquid hydrogen

Liquid hydrogen could be an option as a mid-term solution when liquefaction plants are built and the fuel price comes down. The storage and energy density is slightly better than pressurized hydrogen and the containment system requires less space and weight. The availability and liquefaction costs are however strong disadvantages. Furthermore, storage of liquid hydrogen on-board generates boil-off gasses, requiring frequent and continuous fuel consumption to prevent losses.

Material-based storage

Material-based hydrogen storage (sodium borohydride, ammonia, methanol or LOHC) also requires further development, especially with regards to the hydrogen release systems. There are many advantages for material-based

¹ Swappable liquid hydrogen tank-containers will most likely not be applied in shipping due the safety risks associated with hoisting. This is further discussed in Sub-Activity report 1.1b /27/

² The pressure in liquid hydrogen fuel tanks will increase due to the generation of boil-off gas caused by heat inleak. The pressure will increase even more when there is no continuous gas consumption by the engine. This pressure can normally increase up to values of 7-10 bar, depending on the opening pressure of the pressure safety valve. 5 barg is a typical pressure that you would expect to see for fuel tanks for inland vessels (based on expert judgement and in comparison with LNG fuel tanks).

storage such as high storage/energy densities, relatively safe handling (comparable to diesel or even better, except for ammonia) and possible re-use of existing diesel storage and infrastructure. Methanol and LOHC are stored in the same containment systems as diesel which could potentially be a big advantage when refitting existing inland vessels. A drawback is that some material-based fuels (e.g. LOHC, NaBH_4) require a return cycle meaning that additional containment systems are needed to store the spent fuel on board (taking up space). The application of these technologies and especially the required additional equipment (hydrogen release systems) are however not yet developed for the inland shipping industry or mobility in general and will most likely not be available on a large scale in the next 5-10 years.

Hydrogen bunkering

The feasibility of hydrogen containment systems in IWT are closely linked to the possible bunkering scenarios. Sub-Activity report 1.1b /27/ will further focus on bunkering scenarios and identification of feasible options for storing and bunkering hydrogen on-board of inland navigation vessels.

1 INTRODUCTION

The world fleet is large with 115,000 ships and it will grow in the years to come, with more than 30% up to 2030. IMO's goal of halving CO₂ emissions from shipping by 2050 will lead to a significant restructuring over the next thirty years. The IMO targets and national decarbonization policies are expected to be fundamental drivers for developing low and zero emission technologies in the shipping industry. Next to IMO's goals, the European Union formulated its goals for all sectors in the European Green Deal. It is necessary to find and integrate low-emission propulsion fuels, such as hydrogen, in every part of the transport sector. Hydrogen could significantly reduce emissions, but implementation in inland shipping is new. Hydrogen is the only available zero emission solution for longer distances and high energy needs, but it will remain expensive, especially in the short term. To bring costs down it is absolutely necessary that authorities push for hydrogen technology to be used in vessels and that safety rules & regulations are standardized, which do not exist today.

The Rhine Hydrogen Integration Network of Excellence (RH2INE) is an international programme and consists of public and private parties. Its global aim is to implement hydrogen as a fuel in the inland waterway transport (IWT). On behalf of the consortium of the RH2INE programme, the Port of Rotterdam Authority (PoR) issued an invitation to tender (sub-study 1a: Safety framework conditions) that specifically focusses on safety and regulations related to technical and operational aspects of hydrogen bunkering and transport scenarios for inland navigational vessels. The invitation to tender specifies four sub-activities:

- Sub-activity 1.1a: Identification of hydrogen containment systems for transport and propulsion on board of inland navigational vessels.
- Sub-activity 1.1b: Identification of hydrogen bunkering scenarios for inland navigational vessels.
- Sub-activity 1.1c: Demand study hydrogen bunkering of inland navigational vessels
- Sub-activity 1.1d: Identification of gaps in regulations and standards for the use of hydrogen on board of-, and the supply of hydrogen to inland navigational vessels.

This report focusses on sub-activity 1.1a: *Identification of hydrogen containment systems for transport and propulsion on board of inland navigational vessels*. Efficient hydrogen storage for transport and propulsion on board of inland navigation vessels is an important enabling factor for use of hydrogen as a fuel in IWT. Hydrogen has the highest energy per mass of any fuel, however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density. In this sub-activity report, an overview of storage methods and containment systems including the relevant physical parameters is presented. Specific focus is given to the differences in energy densities and the disadvantages and advantages per storage method/system. This report provides input to sub-activity report 1.1b /27/ where various bunkering scenarios are investigated and provides input to a workshop to identify the most feasible hydrogen storage and bunkering scenarios for inland navigation vessels.

The report starts with an introductory chapter on the various fuels that can be applied in IWT and the relevant criteria & conditions that make a fuel suitable for IWT.

2 ALTERNATIVE FUELS

This chapter provides an overview on the industry's perspective on green fuels in general and on hydrogen in particular. Key drivers as well as potential challenges and incentives need to be reflected to understand the criteria & conditions that make a fuel suitable for IWT.

The industry perspective on alternative fuels and hydrogen has been created based on a number of semi-structured interviews with operators of larger fleets, bunker suppliers and industry associations, a workshop with more than 20 RH2INE members, DNV experience/expert knowledge and several external reports on market adoption of alternative fuels and effectiveness of related programs.

2.1 General perspective on alternative fuels

Hydrogen is one among a number of alternative, more or less green and potentially emission free fuels, such as:

- Power-to-X fuels
 - Electricity/battery
 - Hydrogen (pressurized, liquid or material-based)
 - Ammonia
 - Methanol
 - Synthetic diesel
 - Synthetic gas (Synthetic LNG)
- Biofuels
 - Biodiesel
 - Hydrated vegetable oil (HVO)
 - Ethanol
 - Biogas (Bio LNG)

which can be applied for inland waterway vessels. Hence, a general perspective on alternative fuels shall be taken before looking at hydrogen in particular. The alternative fuel pathways for Power-to-X fuels and Biofuels are given in Figure 1 & Figure 2, respectively.

Alternative fuel pathways (1/2) – Power-to-X fuels

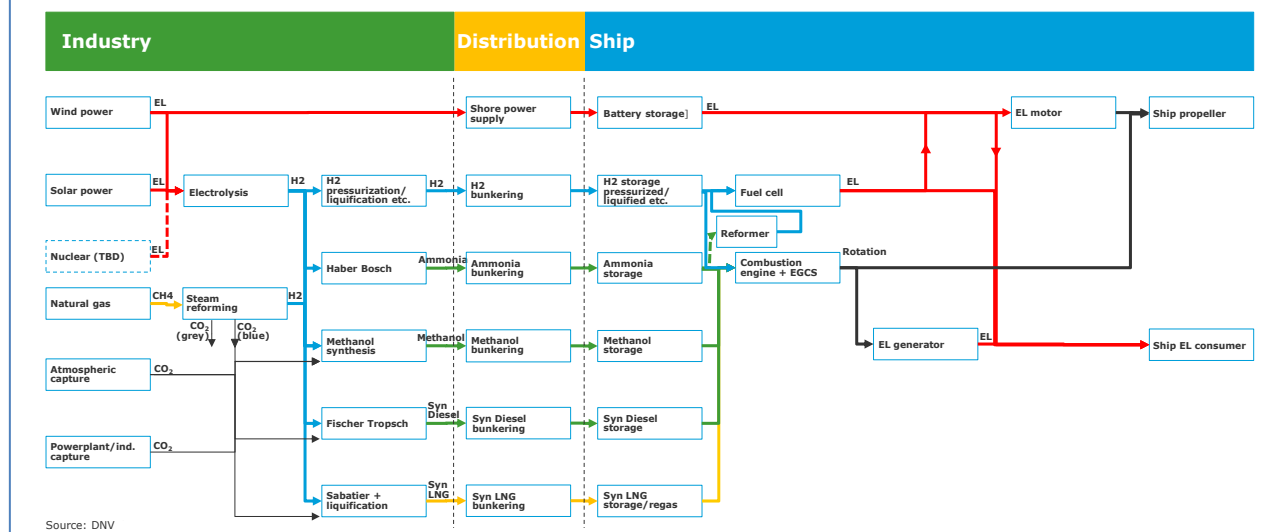


Figure 1: Alternative fuel pathways – Power-to-X fuels

Alternative fuel pathways (2/2) – Biofuels

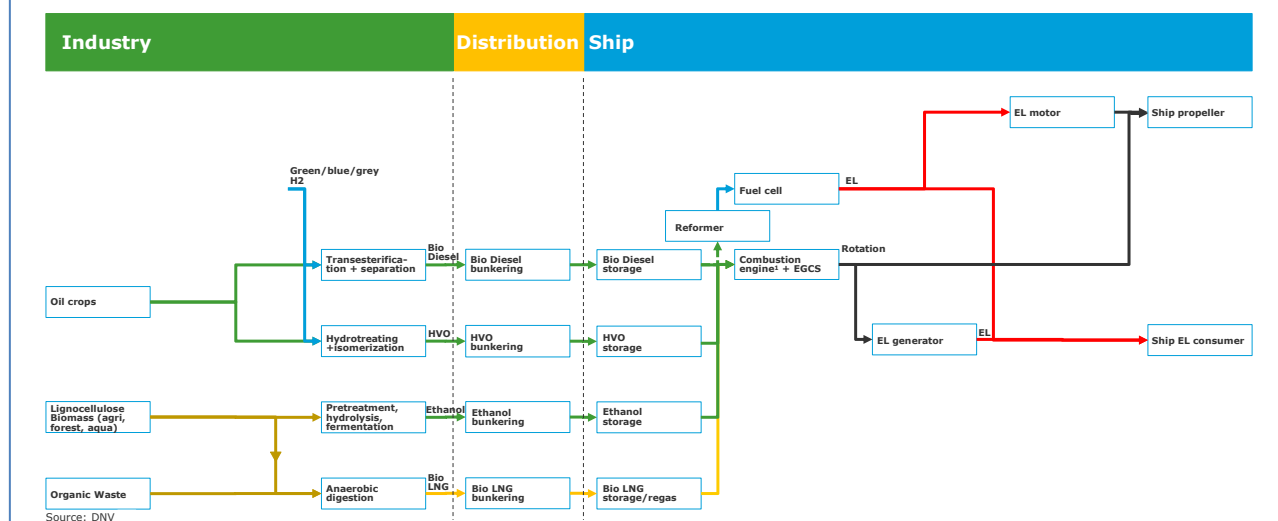


Figure 2: Alternative fuel pathways – Biofuels

Effectively all interviewees acknowledge the societal requirement to the IWT industry to further reduce emissions over the coming years. Most stress the efforts they have been or are taking to meet the stage V requirements of the EU emission regulation for non-road mobile machinery (NRMM)³, which causes significant investment requirements for retrofitting of existing vessels respectively higher newbuilding costs. Still, the industry regards the need for emission reduction generally positive, also considering favourability compared to other means of transport, if new regulations safeguard a level playing field also vs. rail and road transport. According to a survey of the Dutch IWT association BLN-Schuttevaer about 95% of their members have a positive view on green fuels. There is a general understanding among

³ Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC

interviewees that, if every operator had to use green and potentially emission free fuels based on the same and stable regulatory boundaries, the overall profitability of the industry would be largely unchanged.

Besides investments into stage V compliance, a number of ship owners have invested in innovative, greener technology already. E.g. the Dutch Danser Group has decided for a first LNG-fuelled push-barge combination in 2013, which assumed service in 2015. By now there are about ten inland waterway vessels running on LNG. A-rosa will receive a river cruise newbuild with hybrid technology. Further projects using alternative fuels or propulsion concepts are currently being pursued, e.g. by HTS Group, by HGK, by Future Proof Shipping, the HydroTug of BeHydro for the Port of Antwerp and the hydrogen fuelled water taxi of the SWIM consortium for Rotterdam.

Asked for decision criteria on green fuels compared to conventional fuels respectively between different green fuel options interviewees name the following aspects, which are partly interlinked:

- GHG compliance
- Technology readiness
- Operability
- Regulation
- Availability
- Business case

GHG compliance

As Figure 1 and Figure 2 above show, alternative fuels have different shades of green respectively result in different degrees of emission reduction compared to conventional fuel. Not all of the alternative fuels are actually emission- or at least CO₂-free. CO₂ or other greenhouse gas (GHG) emissions can occur during fuel production (e.g. grey hydrogen from steam reforming of natural gas, biodiesel from palm oil plantation on deforested land) or during combustion (e.g. combustion of methanol without CO₂ capturing). Hence, the compliance of the different fuels with existing and future regulation may differ and will be a key criterion for owners in order “not to bet on the wrong horse” – a fuel which may appear compliant (green) today could be subject to regulatory limitations in the future.

In view of the regulatory treatment of achieved emission reduction of the various alternative fuels, interviewees shared the following considerations:

- Which emissions will the regulator cover by what means? Which will be addressed by market-based measures, which by direct regulations (e.g. phase out of technologies, limitation of power, emissions etc.)?
- Will the regulator be technology open and incentivise an emission reduction, not a specific technology?
- Will the achieved emission reduction be acknowledged for the investment horizon or will the acknowledged effect be reduced due to shifting baselines?
- How will emission costs of the conventional technology be priced over the investment horizon?
- How will incentives as investment CAPEX (Capital Expenditure) subsidies (direct grants, favourable credit conditions) develop over time? Will they decrease following a technology cost digression or increase as the regulator realizes that more incentives are needed to achieve the required emission reduction?
- Will the regulator safeguard a level playing field e.g. between different means of transport and across countries?

Interviewees call for reliability of regulatory decisions. The clearer the regulators give their direction, ideally for a significant time share of the investment horizon, the higher is the interviewees' willingness to take risk of alternative

technology and fuel as opposed to conventional technology and fuel. Though, several interviewees mention examples of earlier regulations, which have been postponed or were less ambitious than initially announced, causing disadvantage for early movers.

Technology readiness

Second criterion mentioned by most interviewees is technology maturity. Whereas there is typically some willingness to test promising new technologies (and fuels), the technology needs to be available latest once the newbuild or retrofit project starts. However, most owners would decide for a technology only, if it has proven operability and certain lifetime in other commercial applications. Tests on laboratory scale and tests on land are typically not regarded as sufficient to decide for implementation of the technology on a vessel (with more difficult maintenance etc.). Temporary test of few thousand running hours are typically not regarded as sufficient to build confidence for a commercial decision on a significant investment. Ship owners often look at test installations of new technology at reputable ship owners known for their technical competence. Confidence also increases with the reputation and financial strength of the technology provider. Ship owners would ask if the provider has the financial strength and strategic interest to overcome initial challenges of the technology and be available for after sales service for at least five years. – Technology maturity of various alternative propulsion concepts and involved technology differs. Some technologies are mature with hundreds of installations on vessels (e.g. LNG technology), while others have not left laboratory scale tests.

Operability

Third criterion mentioned by the interviewees is ease of operation or operability. The alternative technology and fuel shall imply as little adverse effects on normal vessel operation as possible when compared to conventional propulsion technology and fuels or even imply positive effects. This is a wider field comprising aspects as:

- loss of cargo space or payload
- increased safety distances limiting simultaneous operation (cargo operation, presence of passengers)
- increased bunkering frequency or additional time required for bunkering
- reduced engine flexibility (low-load operation, ramp-up to peak load)
- increased maintenance
- special requirements to qualification and number of crew

Regulation

The criterion regulation relates to the permission process of applied technology and bunkering operation in view of safety. As regulation is typically not clearly defined for novel technology and fuels (especially low flashpoint fuels), the first applications regularly needs to be permitted on case-by-case basis, whereas responsibility of potentially relevant authorities is not always clear and lack of examples or guidelines may lead to increased requirements, both resulting in uncertainty with regard to duration of the permission process and costs of the solution (CAPEX but also Operating Expenditure (OPEX) implications). This is a clear barrier for application of innovative alternative fuel technology compared to conventional technology.

Availability

The fifth criterion stressed by the interviewees is the availability of the alternative fuel. This relates to fuel production as well as to provision of bunkering infrastructure in a sufficient number of ports in the operating area. Dependency on single suppliers is regarded as a clear disadvantage, even if the supplier (fuel producer and bunkering company) is financially sound and regards the alternative fuels as strategically relevant. All alternative fuels require setting up of new bunkering infrastructure. Some even require setting up of new fuel production capacity. Especially for the bunkering infrastructure the typical chicken or the egg problem exists, with ship owners potentially waiting for suppliers before taking an investment decision and suppliers waiting for a critical mass of ship owners. This applies even more as the investment into LNG bunkering infrastructure has started about 10 years ago, while the number of LNG fuelled vessels is still limited. Many potential suppliers of alternative fuels may be more cautious now based on the experience with LNG.

Business case

Whereas the business case is mentioned last in the order of criteria here, it is finally the most comprehensive and important one as it is influenced by all other criteria listed above.

Nearly all interviewees stressed the business case as key criterion for the fuel choice decision. Their companies operate inland waterway vessels to earn money. Looking at the revenue side of the business case first, several operators across different cargo segments outline that their customers (cargo owners) do not have an increased price willingness for greener transports, as long as a cheaper conventional alternative exists. Several operators tried charging (little) mark-ups on the freight rate for reduced emissions (e.g. due to early introduction of stage V of the European NRMM regulation) but failed as cheaper operators were available. In turn, this means that higher costs affecting the entire industry can most likely be passed on to customers – at least to the degree they affect the least affected operator. Looking at the cost side, most interviewees took a total cost (lifetime cost) perspective, i.e. considering both investment CAPEX as well as ongoing OPEX incl. fuel costs. Interviewees concluded that if alternative fuels don't result in increased revenue for the time being, their total costs must not (significantly) exceed costs of the conventional propulsion system and fuel. While the investment CAPEX for vessel newbuilding or retrofit (required engine exchange after 15-20 years) is typically higher for vessels with alternative fuels, their OPEX incl. fuel costs may be lower over the vessel's lifetime. This may originate from lower fuel prices (the assumption can be made for LNG compared to diesel over a longer time horizon; temporarily biodiesel was also cheaper in some occasions than conventional diesel) or lower emission costs, if assuming that emissions (probably beginning with CO₂) will be priced in future. Of course, also investment CAPEX subsidies as direct grants e.g. from EU and/or national government or reduced capital costs due to favourable credit conditions (backed by the European Investment Bank or national export credit agencies or promotional banks with governmental shareholder) may help balancing the total costs of the alternative fuels case vs. the conventional fuel case. All in all, nearly every potential owner of a vessel newbuild or retrofit will decide for a greener, emission reduced or emission free propulsion technology and fuel only, if he assumes a positive business case over the vessel's lifetime. And the business case is decided on the cost assumptions rather than on the revenue assumptions.

It appears evident that the six criteria mentioned by the interviewees are partially overlapping, e.g. technical challenges have operational implications and cost impact.

An alternative but effectively similar categorization of barriers for innovation uptake related to greening technologies for inland waterway vessels is provided in the PROMINENT report "D1.3 Analysis of barriers and facilitating factors for innovation uptake" prepared by Ecorys in 2015, which is probably the most specific report on barriers and incentives related to inland waterway vessels:

- Technical: Barriers caused by immaturity of technology or operational requirements

- Legal: Barriers caused by regulations and laws
- Financial: Barriers caused by access to capital and business case
- Knowledge: Barriers caused by lack of expertise or skills
- Market: Barriers caused by market conditions, infrastructure and the supply chain
- Cultural: Barriers caused by behavioural routines

All above mentioned criteria and barriers generally apply to both vessels newbuilds with alternative, greener and potentially emission free fuels as well as to retrofits of existing vessels. The latter are typically technically more challenging and the business case may be less favourable, as extra costs compared to conventional propulsion technology and fuels are higher, the investment horizon may be shorter and access to capital may suffer from a lower security value of the mortgaged vessel.

2.2 Perspective on hydrogen

The potential of hydrogen as fuel for inland waterway vessels on the Rhine follows the criteria mentioned by the interviewees and elaborated for alternative fuels in general in the previous paragraph. However, it needs to be acknowledged that some aspects relate to various criteria, as e.g. regulation is affecting the business case.

GHG compliance

Whereas hydrogen can be grey (produced by steam reforming of natural gas without CO₂ capture), blue (produced of natural gas with CO₂ capture) or green (produced by electrolysis of water with green electricity) and green hydrogen has a minority share yet, all interviewees assume future hydrogen to be green and thereby truly GHG free in Western Europe. This seems in line with the EU's and the national governments' agendas. Hence, hydrogen as fuel for inland waterway vessels can be regarded as fully GHG compliant. Thereby it can be regarded as equal to electricity/battery and has some favourability compared to most other alternative fuels.

Technology readiness

Considering both the interviewees' perspective and numerous external sources the technology readiness of hydrogen as ship fuel appears overall medium at best. Whereas hydrogen in combination with fuel cells is used in silent running of submarines today and there are several applications on commercial vessels globally, experience with applications on inland vessels is very limited yet. There are a few application cases with hydrogen fuel cell technology (e.g. passenger boat "Alsterwasser" in Hamburg) which have been implemented and more projects are currently being implemented.

The first technological challenge is the storage of hydrogen. Especially gaseous storage in pressure levels between 300 and 500 bar suffers from a very unfavourable gravimetric energy density. While hydrogen itself has about three times as high energy density per kg compared to diesel, one ton of hydrogen (equals about 3 tons of diesel) currently requires a tank weight of nearly 20 tons, i.e. the gravimetric energy density including containment system is about one seventh of the one of diesel (see Figure 3). Liquid storage in super insulated vacuum tanks at about -253°C has the potential to achieve a gravimetric energy density of about half the one of diesel. Hydrogen storage in the form of sodium borohydride (NaBH₄) may result in a further improvement in the future. However, technology is in the development stage still and may take 5-10 years to commercial viability.

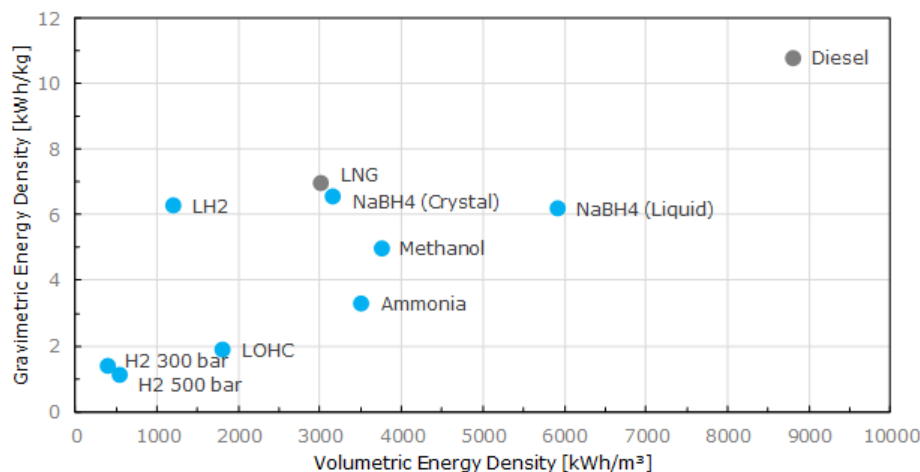


Figure 3: Energy density of hydrogen in different forms incl. storage system

The second technological challenge are the yet limited durability and power output of existing fuel cells. Fuel cells with 300 kW have been implemented on submarines, which would require a combination of a number of fuel cells for mid-sized and larger inland waterway vessels. The durability of polymer electrolyte membrane (PEM) fuel cells still appears significantly shorter than of combustion engines. 5,000 hours correspond to about one year of vessel operation. Hence, frequent replacement (after technical downtime) is to be expected. Furthermore, fuel cells yet suffer from limited load flexibility, which requires a (costly and heavy) combination with significant battery capacity for peak load and possibly a selective use of only one fuel cell (of a batch) for low-load operation downstream and in port. Manufacturers of fuel cells currently work on all three challenges and improvement can be expected for the coming years following an industrial learning curve supported by the numerous pilot applications across various industries.

A third aspect with regard to technology readiness are dual-fuel hydrogen combustion engines, which could be an alternative to fuel cells. Such engines are currently being developed and commercialized by BeHydro, a joint venture between Anglo Belgium Corporation and CMB. The engines shall run on 85% hydrogen and 15% MGO (Marine Gas Oil) as pilot fuel. While the first application is planned for a tug in the Port of Antwerp, overall technology readiness appears to be behind that of fuel cells yet. Furthermore, also pure hydrogen combustion engines are being developed and will be implemented in some pilot projects (e.g., HyMethShip).

Operability

Related to the energy density challenge outlined above is the effect on ship weight respectively payload, if hydrogen is used as ship fuel. Depending on vessel type, engine size, consumption, operating profile and bunkering frequency, the effect may be significant. Assuming an unchanged bunkering frequency, a vessel, which has been bunkering 10 m³ diesel (e.g. smaller dry cargo vessel or tanker) would lose about 50 tons of payload if carrying the same energy amount of hydrogen in pressure tanks. For a vessel, which has been bunkering 50 m³ diesel (e.g. larger push boat) the ship weight would increase by about 250 tons. Weight increase respectively loss of payload are a significant disadvantage, especially in case of shallow water.

The effect could be compensated to some degree by an increased bunkering frequency. Instead of one bunkering per round trip, the vessels would need to bunker several times, whereas the tank would need to be dimensioned for the leg with the highest consumption, e.g. Rotterdam to Kehl if this would be the first stop of a liner service from Amsterdam, Rotterdam, Antwerp (ARA) ports to Basel. As outlined before, most operators favour Ship-To-Ship (STS) bunkering during operation in order not to lose time and regard the need for additional bunkering stops as clear disadvantage of

hydrogen. However, some interviewees acknowledge that one or even two bunkering stops per week might be acceptable, if they were short and led to little time loss.

Today, however, bunkering rates of gaseous pressurized hydrogen yet appear too low for that (note that literature and market insights are somewhat contradictory in this aspect, this aspect is discussed in more detail in sub-activity 1.1b), resulting in unfavourably long to bunkering times even for the reduced energy amounts required at increased bunkering frequency. This may be overcome by increased bunkering rates of liquid hydrogen in the future (1,000-4,000 kg/h) or by using swappable hydrogen tanks which are pre-filled at land and loaded onto the hydrogen fuelled vessels within few minutes.

Such swappable tanks (both as pressure tanks of 300 bar as well as super insulated vacuum tanks for liquid hydrogen) are currently being developed and tested in first applications. Whereas they inevitably contribute to the above-mentioned payload effect and thereby call for higher bunkering frequency, they appear to be a viable solution in particular for container vessels. Their flexibility (carry just as much tank volume as you need) is an additional advantage compared to fixed tank installations. However, a technical solution for the application on vessel types other than container vessels still needs to be found. It remains to be seen, if these other vessels types will have to call container terminals for swapping of tank-containers then or if a separate infrastructure for swapping tank-containers will be build up for the other vessel segments.

Overall hydrogen as a fuel bears a number of operational challenges compared to both conventional diesel fuel but also to some of the other alternative fuels. Whereas they are not regarded as show-stopper by the interviewees they are at least regarded as disadvantage.

Regulation

Hydrogen is a low-flashpoint fuel, which is not yet covered by established regulation for ship design and (especially bunkering) operation. Until such regulation will be developed and adopted by the relevant authorities, the first projects require permissions on case-by-case basis. For LNG the process from first permissions on exceptional basis to established regulations has taken about one decade. Still not all ports are prepared to grant permissions for LNG bunkering. It can be assumed that the same process will be somewhat quicker, also as LNG as another low-flashpoint fuel has prepared the way and helped authorities clarifying the required stakeholder involvement, risk analyses and the permission process. However, it still may take more than five years until a common regulation on ship design and (bunkering) operation for hydrogen as ship fuel will be established. In the meantime, projects will have to deal with case-by-case decisions, which require significant management attention and bear risks for the business case in terms of both CAPEX and OPEX.

This is clearly a disadvantage of hydrogen compared to conventional fuel and higher flashpoint alternative fuels.

Availability

As outlined before, the availability of relates to fuel production as well as to provision of bunkering infrastructure in a sufficient number of ports in the operating area during the investment horizon.

Currently the production of green hydrogen from renewable electricity is limited in Europe and several industries (as e.g. steel and chemical industry) have an increasing demand and possibly a higher paying power than the IWT. However, stimulated by the political development of the past 18 months with the European Green Deal of December 2019 and numerous national hydrogen strategies in the EU member states unveiled, it can be assumed that the production of green hydrogen (from on- and offshore wind and photovoltaic) is ramping up quickly over the coming years. Suppliers will be both utility companies, established gas manufacturers with experience in cryogenic and pressurizes gases, and

possibly traditional oil majors on their way towards new businesses, probably also joint ventures between different types of players. The risk of dependency on single suppliers for pressurized and liquid hydrogen appears limited. For material-based hydrogen (e.g. LOHC or sodium borohydride) this may be different for the next ten years.

Setting up and operating infrastructure for hydrogen bunkering is a different business than the fuel production. Given the slow uptake of LNG as fuel for (inland waterway) vessels and considering the yet immature hydrogen bunkering technology, it appears questionable if suppliers of conventional bunkering along the Rhine are willing to take the significant investment risk of setting up hydrogen bunkering infrastructure. This especially applies, if they had to own a large number of swappable tank-containers. Instead, a breakthrough of hydrogen supply to inland waterway ships will most likely require strategic engagement of a large industrial player (gas producer, utility company, oil or energy major), who is not only aiming at supplying (moderate amounts) of green hydrogen to inland waterway vessels but also to large consumers in the steel and chemical industry along the Rhine. First ports with hydrogen bunkering infrastructure (for the time being swappable containers moved by container bridges) will be most likely one of the ARA ports, followed possibly by ports with container terminals in the Ruhr area.

Direct grants or favourable financing conditions supporting the investment CAPEX in line with EU and national hydrogen strategies might help turning the business case for a potential hydrogen bunker supplier positive.

Even though it appears likely that hydrogen bunkering infrastructure will be available in an ARA port and at least in the Ruhr area within the next few years, ship owners would face a limited number of potential suppliers and thereby a supply and a price risk. Such a supply risk has stopped the passenger boat “Alsterwasser” in Hamburg, which ended service after hydrogen supply had stopped. Hence, owners need to build on financially sound suppliers with strategic interests in developing this new business area and fix hydrogen prices with them for a significant share of the investment horizon.

Overall availability of hydrogen for inland waterway vessels is and remains more challenging than availability of conventional diesel fuel, but there seems no disadvantage compared to other emission neutral or low flashpoint alternative fuels.

Business case

The business case is the primary criterion in the decision process for alternative fuels and hydrogen in particular. All interviewees named it as the most comprehensive and important criterion, which is influenced by all criteria outlined above.

As previously stated, none of the interviewees would build a business case on a significant mark-up on the freight rates for transportation with alternative fuels. However, some expect to score a little higher in freight tenders and win a few additional customers. This particularly applies for container vessels, which are generally closer to end customers than dry bulk vessels and tankers, and to river cruise vessels of course.

In turn, interviewees would decide for hydrogen only, if the business case is favourable compared to conventional fuels and other alternative fuels from a cost perspective. Today both CAPEX and OPEX for hydrogen as fuel are significantly more expensive than conventional propulsion technologies and fuels. Hence, the business case can only become positive with several regulatory changes respectively governmental incentives and the commitment of a hydrogen supplier with strategic interest in developing the market and willingness to offer green hydrogen in a longer-term contract at conditions below today's regular price levels.

First requirement for a positive hydrogen business case (as well as the cases of other alternative fuels) is that emissions need to result in costs for the emitter. Whereas also the introduction of stage V requirements of the EU NRM had a positive effect for hydrogen compared to conventional fuels, even though targeting NO_x and not CO₂ emissions, a significant impact on the business case would come with introduction of CO₂ prices. Economically it would not matter, if

the price is a result of emission trading or CO₂ taxation, as long as the price is sufficiently high. A price level of about 25 EUR/ton as currently effective in the EU ETS and planned by the German government for the transportation sector from 2021 would have little impact. The planned increase to 55-65 EUR/ton CO₂, equivalent to about 170-200 EUR/ton diesel, would strengthen the business case for hydrogen. The break-even price depends on the individual project and would likely be even higher in many cases.

Second requirement for a positive business case are investment CAPEX subsidies either as direct grant or as e.g. from EU and/or national government or reduced capital costs due to favourable credit conditions (backed by the European Investment Bank or national export credit agencies or promotional banks with governmental shareholder). The Dutch Green Deal for shipping, IWT and ports can be a significant contributor for the hydrogen business case. One of the ambitions is to fit 150 inland vessels with zero-emission power trains by 2030. Besides other measures a European sustainability fund for inland waterway vessels shall be established. As a first step 15 million EUR shall be granted promoting clean engine technology. This comes in parallel to a 79 million EUR programme for retrofitting of existing inland waterway vessels with Selective Catalytic Reduction (SCR) or other Nitrogen oxides (NO_x) reduction technology. A combination of emission pricing and CAPEX subsidies for investment in clean technology, like implemented in the Norwegian NO_x fund, can be considered in order to stimulate penetration of low or zero emission technology (as hydrogen) in a cost neutral way for the governments. However, interviewees stress that technology openness and a level playing field across countries and transport means shall be safeguarded.

Without introduction of emission prices and investment CAPEX subsidies hydrogen does currently not have a positive business case. Neither compared to conventional diesel fuel nor to some other alternative fuels with lower (but not zero) emissions as biofuel. Even a CAPEX digression following an industry learning cost curve would presumably not be sufficient to turn the case. Emission pricing is a prerequisite for the success of all alternative fuels.

2.3 Synthesis

The figure below synthesizes the competitiveness of hydrogen vs. conventional diesel and other alternative fuel options for inland waterway vessels as of today along the six criteria that make a fuel suitable for IWT that were important to the interviewees.

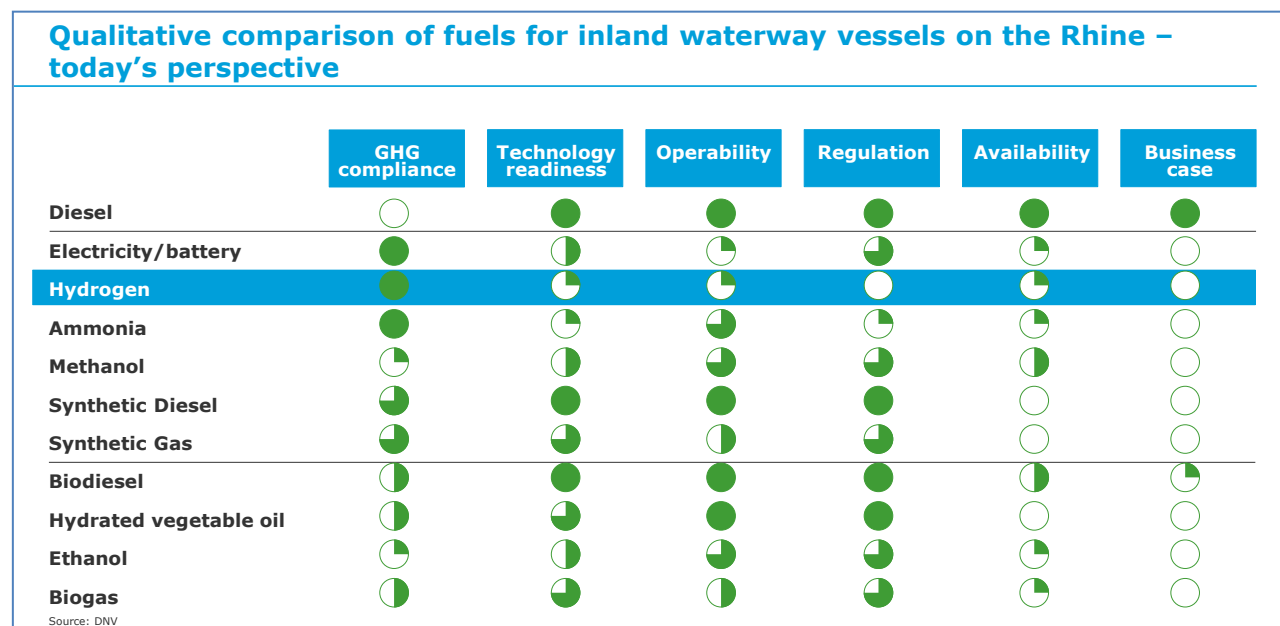


Figure 4: Qualitative assessment of fuels for inland waterway vessels – today's perspective

Hydrogen is, among electricity/batteries and ammonia, the only GHG-emission-free fuel and will have to be part of the solution space, unless other alternative fuels are combined with carbon capture and storage.

With regard to technology readiness hydrogen is inferior to fuels of diesel-like properties burned in combustion engines. This applies both for the use of hydrogen in fuel cells as well as possibly in combustion engines. However, it is at eye level with ammonia and just a little behind electricity/battery technology.

Operability is limited especially due to the gravimetric energy density resulting in reduced payload or higher bunkering frequency with the need for swappable tank-containers due to yet low bunkering rates.

Regulation of ship design and permission process of the bunkering process is yet to be developed, which may, even with the experience from LNG, take five or more years. This seems easier and potentially shorter for most of the other alternative fuels, including electricity/battery and to some degree ammonia.

The availability is limited yet. Same applies for ammonia and electricity as shore power for quick recharging of batteries or even swappable batteries. Though, in line with the national hydrogen strategies, it can be assumed that the production of green hydrogen will ramp up quickly within the next few years and there will be industrial players setting up hydrogen bunkering infrastructure at least in ARA ports and the Ruhr area. However, this may be initially limited to container terminals for swapping tank-containers. Other vessels types may have to accommodate to that unless hydrogen suppliers set up a parallel infrastructure for other vessel types.

Under today's regulatory regime without emission pricing, there is not a business case for any alternative fuel, with few exceptions for biodiesel in the Netherlands due to feed-in requirements. With significant emission pricing, considering also the well to tank emissions of e.g. biofuels or grey hydrogen, and temporary investment CAPEX subsidies, however, there can be a business case for green hydrogen depending on the operating pattern and other above-mentioned drivers.

Looking at vessel types and trade patterns we see a differentiated picture for the future competitiveness of green hydrogen as fuel for inland waterway vessels on the Rhine:

Segments of higher suitability and competitiveness of hydrogen:

- Vessels on fixed trades, liner service or long-term freight contracts
- Vessels on shorter trades
- Vessels operating largely between ARA ports and Ruhr area
- Vessels with limited engine load volatility
- Vessels with limited impact of higher weights
- Container vessels
- Newbuilds and possibly younger vessels of 15-20 years
- Vessels owned by larger owners; incl. governmental

Segments of lower suitability and competitiveness of hydrogen:

- Vessels with irregular trading patterns operating on spot market
- Vessels with long voyages without interim stops
- Vessels with high engine load volatility

- Vessels impacted by higher weights
- River cruise vessels, dry cargo, tanker
- Old vessels, especially if above 20 years
- Vessels owned by single-ship owner

Reference is made to sub-activity report 1.1c for a quantitative assessment of the market potential (demand prognosis) for hydrogen. The following chapters will further focus on the identification of hydrogen storage methods and containment systems for inland navigational vessels.

3 STUDY APPROACH

The approach for the study into hydrogen storage methods and containment systems comprises of the following steps:

1. Literature review based on publicly available information;
2. Review of relevant DNV reports, projects;
3. Internal DNV expert workshop;
4. Review of design standards and technical specifications;
5. Interviews with manufacturers and pilot projects.

These steps are detailed below.

Literature review

As a starting point a literature review was conducted to identify the possible methods and containment systems for storing hydrogen on-board of inland navigational vessels. Information about the working principle, physical parameters, state of development and the advantages and disadvantages of the hydrogen containment systems was found and used to construct the basis of this report. The literature was based on laboratory results, desk-research, pilot projects or applied practices. Some of the latest literature specifically focussing on on-board application of hydrogen was used including:

- HyNed, HyMove, HAN and KIWA, "Hydrogen and hydrogen carriers for inland shipping, 2020
- EICB, "Waterstof in Binnenvaart en Short Sea", 2020
- DUAL Ports, "Feasibility of Hydrogen Bunkering", 2019
- Marigreen, "Perspectives for the Use of Hydrogen as Fuel in Inland Shipping", 2018
- L. Baetcke and M. Kaltschmitt, "Hydrogen Supply Chains, Chapter 5 - Hydrogen Storage for Mobile Application: Technologies and Their Assessment", 2018
- D.Stolten and B. Emonts, "hydrogen Science and Engineering" – vol.2, 2016

The EICB study was also used as a starting point for identifying current hydrogen projects in the shipping industry. The information in this list was supplemented by other literature to obtain more technical information for storing hydrogen onboard inland navigational vessels.

Review of DNV reports and projects

Other DNV projects and those involved were consulted for their insights in on-board storage and bunkering of hydrogen or hydrogen carriers. This allowed for the addition of practical knowledge in the report and further supplemented the knowledge and information of current hydrogen projects in the shipping industry.

Internal DNV expert workshop

An internal DNV expert workshop took place on the 20th of August 2020. Several DNV experts participated in this workshop (from offices in Norway, Germany and the Netherlands) with relevant hydrogen and inland shipping knowledge. Specific expertise comprise of hydrogen containment system technology, bunkering, related safety assessments. The experts participate (or have the lead) in various hydrogen programs & projects, such as the Dutch Hydrogen Safety and Innovation Program, several safety research projects (e.g. the EU funded projects EIHP2, HyApproval, HyWays, H2SusBuild), ongoing Joint Development Project on Maritime Hydrogen Safety (MarHySafe JDP) and several maritime hydrogen projects (e.g Zero-V, HybridShip, and pilots in the Green Shipping Programme). Furthermore, the German representative at the IMO for the further development of the IGF-Code (Interim Guideline for

Fuel Cells) and also responsible for the DNV Class Rules for Fuels Cells (Pt. 6, Ch. 2, Sec. 3) also participated. In addition, one of the participants represented the Norwegian Flag at the IMO for the development of the Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk and is currently working with the approval of hydrogen fuel installations and hydrogen development projects.

The goal of the internal workshop is to discuss available hydrogen storage technologies, current applications and the overall feasibility for use in inland navigation vessels. Specific technical information about containment systems (e.g. about the design, physical conditions) was collected and provided in the months after the workshop and subsequently incorporated in this report.

Design standards and technical specifications

To assess the current common practice for storing hydrogen or hydrogen carriers and the design parameters of containment systems, standards, factsheets, handling manuals and manufacturer information was used including:

- ISO TR 15916 - Basic considerations for the safety of hydrogen systems
- ISO 15399 – Gaseous Hydrogen, Cylinders and Tubes for Stationary Storage
- Hexagon Lincoln - product sheets for pressurized hydrogen storage
- MSC - Recommendations for Carriage of Liquefied Hydrogen in Bulk
- Cryocan – Ammonia storage product sheet
- Linde – Datasheet Ammonia
- PGS 12 – Ammonia storage
- Hydrogenious – LOHC solutions Product sheet
- Methanol institute - Methanol Safe Handling Manual
- EIGA – Recommended practice Manual Refrigerated CO₂ Storage at Users' Premises

Interviews with manufacturers and pilot projects

Finally, all project initiators of identified hydrogen projects in the shipping industry were contacted for technical project details about the storage and bunkering of hydrogen and to give their insight in applying hydrogen in the inland shipping industry. 11 parties were interviewed including:

- | | |
|-------------------------|--------------------------|
| • NEDSTACK | • Eifer |
| • Enviu | • Hydrogenious |
| • H2 Fuel Systems | • Vattenfall |
| • LEC | • Hexagon Lincoln / HYON |
| • Future Proof Shipping | • Voyex |
| • Port of Amsterdam | |

The interviews and the project information were used as input for this report but are discussed in sub-activity report 1.1b /27/ (hydrogen bunkering scenarios).

4 STORAGE METHODS

This chapter describes the types and methods most commonly used for hydrogen storage. The different methods to store hydrogen can be categorized into two types; Physical-based and Material-based. The figure below gives an overview of the different hydrogen storage methods and the categorisation of the two storage types. The subsequent paragraphs describe the storage types in more detail and include a concise description of the main working principles.

Physical-based			Material-based	
Pressurized	Cryo-compressed	Liquid	Hydrides • Liquid organic hydrogen carriers (LOHC) • Metal hydrides: • Sodium Borohydride • Lithium • Magnesium • Compounds • Methanol • Formic acid • Metal hydrides • Ammonia	Adsorption • Carbon materials • Zeolites • Nanostructures • Clathrates

4.1 Physical-based

Physical-based storage relies on the principle of changing temperature and/or pressure without changing the composition of the substance (hydrogen). Cooling and compression are used to increase the volumetric and gravimetric density of hydrogen in order to store it in compact containment systems. Physical-based storage is currently the most developed storage type and is most commonly applied in industry and in mobility. The following three methods can be distinguished;

4.1.1 Pressurized

Pressurized storage is one of the most common and simple storage methods. Hydrogen is compressed in order to increase the volumetric storage density and stored in pressure containers. Current systems consider 200-500 bar and possibly even higher pressures in the future.

4.1.2 Liquid

Hydrogen is cooled to its normal boiling point at around -253 °C (ambient/moderate pressures). At these conditions, hydrogen becomes liquid and has an energy density of 8 MJ/l [1]. Hydrogen in this state is also called cryogenic. Over time, the temperature will increase due to heat inleak and the pressure in the containment system will increase and needs to be vented (boil-off) to prevent overpressure. To minimize boil-off/losses (BOG) the temperature must be maintained below the boiling point as much as possible. Therefore, containment systems are usually well-insulated.

4.1.3 Cryo-compressed

Cryo-compressed hydrogen is a combination of pressurized and liquid (cryogenic) hydrogen. Hydrogen is stored at cryogenic temperatures but allows for slightly higher temperatures and a high pressure inside the cryogenic vessel. The allowance of higher pressures reduces boil-off losses as hydrogen can be stored longer before venting is needed.

4.2 Material-based

Material-based hydrogen storage relies on the bonding of hydrogen molecules to other molecule structures or on the surface of other materials. Material-based storage is achieved in hydride storage or by adsorption.

4.2.1 Liquid organic hydrogen carriers (LOHC)

Storage in LOHC relies on the principle of binding hydrogen in a liquid organic substance. Here LOHC, dibenzyltoluene (H0-DBT) and perhydro-dibenzyltoluene (H18-DBT) are considered. H0-DBT does not contain any hydrogen and is the dehydrogenated form of LOHC (LOHC⁻). H18-DBT is the hydrogenated form of LOHC (LOHC⁺) and contains 9 molecules of H₂ /17/. LOHC is referred to as a carrier liquid and just the medium to store hydrogen.

4.2.2 Methanol

Another possible application of a hydrogen fuel in inland shipping is methanol, which is a liquid between -93°C to 65°C at atmospheric pressure /22/. Methanol is already widely stored and transported and infrastructure is already developed and available to some extent.

4.2.3 Metal hydrides

One (light) metal hydride that has recently gained attention for its possibility to store hydrogen is sodium borohydride (NaBH₄). Hydrogen storage in powder form (such as NaBH₄) has been subject to research earlier, however, recently it gained attention again /3/. A start-up company, H2 Fuel Systems, together with the Technical University of Delft and the University of Amsterdam, is further developing the technology of storing hydrogen in NaBH₄. They developed a method with high hydrogen extraction efficiency which releases hydrogen from the NaBH₄ by mixing with (pure) water over a catalyst /19/. NaBH₄ is a solid substance, similar to salt, is strongly alkaline and corrosive but can be handled safely with protective clothing /20/.

Other metal hydrides such as Lithium, Magnesium, Silicium or compounds (combination of metals) still require much more development. Only Silicium is commercially offered by HySil labs but DNV was not able to successfully approach them for more information. For these reasons, only sodium borohydride is further considered as a metal hydride in this study.

4.2.4 Ammonia

Ammonia (NH₃) is a common industrial product used worldwide in many applications (fertilizer, cleaning products). Recent developments are to use it as a fuel or to convert back to hydrogen for use in fuel cells. Production and storage is well developed in the industry and storage technologies have a high maturity. Ammonia is gaseous at ambient conditions but becomes liquid when stored above its vapour pressure of 8.5 bar (at 20°C) or when it is cooled to -33 °C (at ambient pressure) /12/.

4.2.5 Adsorption

Adsorption relies on the hydrogen molecules to attach to a material. High surface materials are most effective, hence porous materials are usually used. Some of those materials are listed below:

- Carbon materials
- Zeolites
- Nanostructures
- Clathrates

Adsorption is still in an early R&D stage and is still mostly done at lab scale. Furthermore, no applications in the shipping industry were found. Adsorption is therefore not further considered in this study.

5 CONTAINMENT SYSTEMS

This chapter describes the containment systems for different hydrogen storage methods as described in the previous chapter. For each storage method, a description of possible containment systems is provided including the working principle, an indication of the different sizes and the operating conditions such as pressure, temperature and storage density. In addition, some advantages and disadvantages are discussed and inland shipping project examples are provided.

5.1 Physical-based storage

5.1.1 Pressurized

Pressurized hydrogen is stored in a pressure vessel at different pressures. There are various vessel sizes and the material largely depends on the storage pressure and the application. The working principle is relatively simple. The system consists of the pressure vessel and is fitted with a valve. The valve is used for filling and emptying the vessel and is also fitted with a pressure safety relief system in case the pressure becomes too high. The figure below gives a schematic overview of the system.

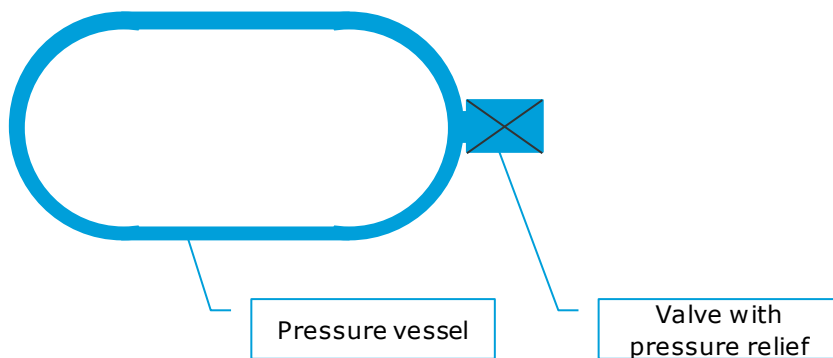


Figure 5: Schematic overview of a hydrogen pressure vessel.

Pressurized hydrogen vessels can basically be categorized in four types /4/.

Type I: a metal container

Type II: a metal container wrapped with metal hoops or fibre wrapped (glass aramid or carbon) for reinforcement

Type III: a container made from composite material (fiberglass, aramid or carbon fiber) with a metal liner (aluminium or steel)

Type IV: a container made from composite material (fiberglass, aramid or carbon fiber) with a non-metallic liner (polymer)

Type IV vessels are most promising for mobile applications due to many advantages over the other types. Type IV vessels can withstand high pressures while maintaining light weight systems, they are less susceptible to fatigue cracks due to charge/discharge cycles and large diameters are possible. These advantages however come at higher costs /5/.

Hydrogen pressure vessels are usually spherocylindrical shaped and hollow and can be found in many sizes. For small hydrogen quantities of a few to tens of kg's, single tanks are used. For higher quantities (up to approximately 1,000 kg) multiple vessels are used and can be fitted into a standard shipping container. The pressure vessels can be used both as a fixed on-board storage system but could also easily be swapped. Examples of standard (swappable) systems are

cylinder racks and ISO container frames which can be fitted with either upright cylinders/bottles, tube vessels or flanged pipe systems. To maximize space utilization, the voids between larger vessels are filled with smaller vessels. The figure below gives an indication of the three systems.

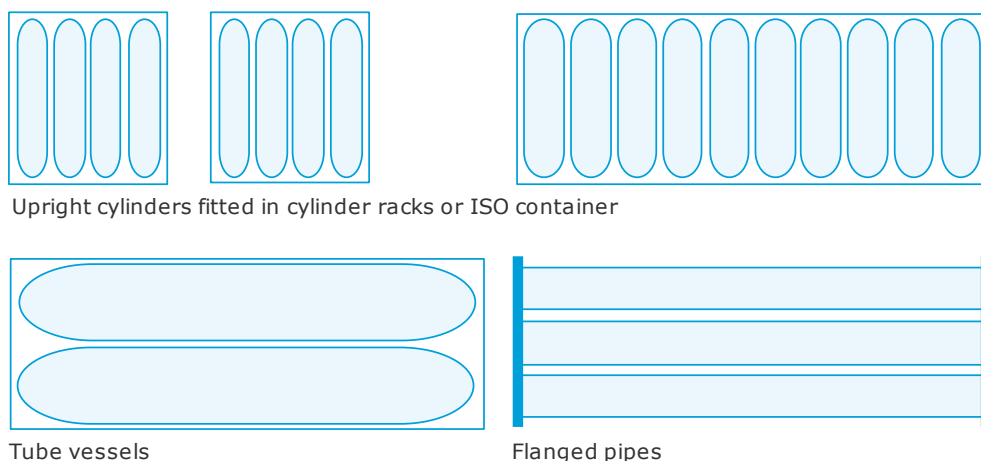


Figure 6: Indication of pressurized hydrogen vessels in cylinder racks or ISO container frames.

The system storage capacity depends on the operating pressure and can vary from only a few bars to 1000 bar. Currently, pressurized storage for mobility is set around 200-500 bar and is possibly increased to 500-1000 bar in the future. Certified type IV storage vessels are already available below 700 bar. The storage densities depend on the pressure and temperature and are at ambient temperature approximately 16 kg/m³ (2.2 GJ_{hvh}) at 200 bar, 22 kg/m³ (3.2 GJ_{hvh}) at 300 bar and 43 kg/m³ (6 GJ_{hvh}) at 700 bar. The figure below indicates the storage density in kg/m³ and MJ/m³ (based on higher heating value; 142 MJ/kg) at different pressures and at ambient temperature.

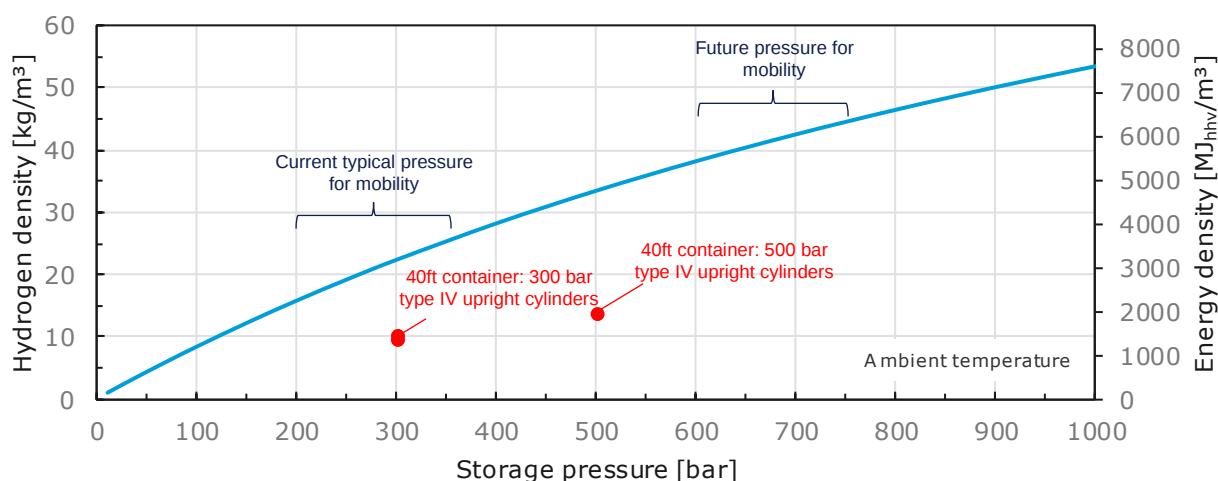


Figure 7: Overview of hydrogen density at different pressures.

The figure above does not include the volume and weight of the storage system itself. For example (using manufacturer data), a 40ft ISO container, fitted with 300 bar (type IV) upright cylinders and a storage capacity of 835 kg, weighs 20.2 tons in total (including hydrogen). The storage density including the containment system is 10.25 kg/m³ (1.44 GJ_{hvh}/m³). This is also indicated in the figure above for a 300 and 500 bar 40ft. container.

Pressurized hydrogen is normally stored at ambient temperature. However, during filling the temperature will increase as the pressure increases (adiabatic compression). The increasing temperature should be monitored as it could influence the integrity of the storage vessel. Especially polymers are sensitive to high temperatures, e.g. Type IV (manufacturer interviews). Excessive adiabatic heating is normally prevented by controlling the flow rate.

Other forms of pressurized containment systems

In addition to the regular type I-IV vessels, reinforcement with an internal (space filling) skeleton is also possible to withstand high pressures and reducing the wall thickness. These are however still in early development.

As an alternative to the hollow pressure vessels hydrogen can also be stored in capillaries (e.g. glass tubes). Each capillary acts as a pressure vessel containing a small volume of hydrogen and are therefore presumed to be safer as less hydrogen is released during an incident. However, the technology is pre-mature, durability of (glass) capillaries is disadvantageous over many (dis)charge cycles and to release hydrogen from the capillaries requires a large amount of energy [1].

PROJECT EXAMPLE

MS Maas Container ship

Fuel type	Compressed hydrogen
Vessel type:	Type II
Storage system:	2x 40 ft. tube-containers
Placement:	Above deck
Storage capacity:	900 kg
Pressure:	300 bar
Temperature:	Ambient



Information based on interviews with Future Proof Shipping

5.1.2 Liquid

Containments systems for liquid hydrogen, also called “dewars” rely on the principle of minimizing heat transfer with the surroundings by using a high degree of insulation. Hydrogen is a liquid below -253°C and should be stored in highly insulated vessels⁴. After liquification, hydrogen is not actively cooled in the storage container and an increase of temperature results in hydrogen shifting from the liquid to the gas phase. This will lead to an increase in pressure which requires regulated venting of the gaseous hydrogen to prevent overpressure. The associated hydrogen losses are called “boil-off” and are minimized by maintaining a low temperature in the storage vessel.

⁴ Because of the extremely low temperature liquid hydrogen is often referred to as cryogenic. The super insulated vessels, capable of handling such temperatures, are therefore also referred to as cryogenic vessels.

A liquid hydrogen storage vessel typically consists of (1) an inner tank, made of a metallic or composite material, to contain the liquid hydrogen, (2) multiple layers of insulation; layers of metallic foil, separated by glass wool or a polymer (e.g. PIR, PUR), (3) a vacuum space (sometimes with perlite spacers) and (4) an outer tank. This form is also called "superinsulation". In addition, the vessels are fitted with safety systems, valves and measuring systems to monitor important parameters such as pressure and temperature. In combustion engines or fuel cells, hydrogen is consumed in gaseous form. This requires an additional regassification installation and possibly a small pressurized buffer of gaseous hydrogen. /1//6/

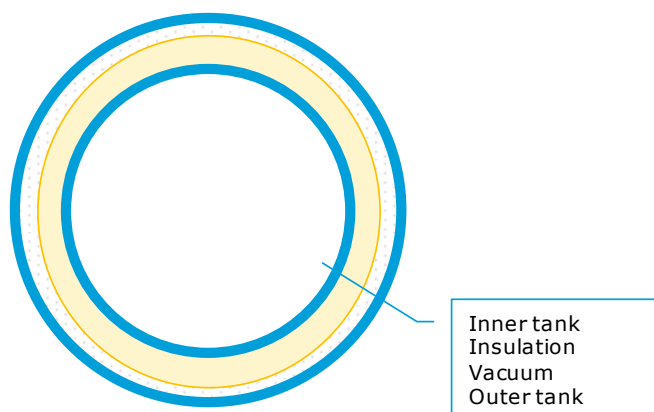


Figure 8: Schematic overview of a liquid hydrogen storage vessel.

The storage vessels can be found in many shapes and sized but are usually spherical or spherocylindrical shaped. The selection is a trade-off between the lowest surface to content ratio and ease of transport. Only a few producers of liquid hydrogen and manufacturers of liquid hydrogen tanks exist. They store hydrogen on-site in bulk /4/. With the recent interest in hydrogen as a renewable energy carrier, plans are also made for liquid hydrogen bulk transport in bunker ships.

Some current designs for hydrogen bunker ships rely on an IMO type C system for storing liquid hydrogen /7/. This is a super insulated storage system allocated to dangerous goods of class 2.3 (toxic gasses). This is however not required by the Maritime Safety Committee (MSC) who deals with all matters related to maritime safety and maritime security which fall within the scope of IMO /6/.

An example of a liquid hydrogen bunker ship is presented by Moss Maritime. The figure below gives an indication of some specifications.

- Length overall: Abt. 137.0 m
- Breadth mld: Abt. 19.8 m
- Cargo (LH2): 500 tonnes
- LH2 loading: 600 m³/h
- LH2 unloading: 300 m³/h
- Cruising range: 20 000 nm
- Speed: 15 knots
- Power system: TBD ¹⁾
- Accommodation TBD ¹⁾



Figure 9: Conceptual design of a liquid hydrogen bunker ship /7/.

Other mobile applications include 45-64 m³ semi-trailers, capable of carrying 3150-4480 kg of hydrogen and similar in design as described earlier /8/. Another possibility is the transport of liquid hydrogen in an ISO tank-container, which can be hoisted /9/. Examples of swappable liquid hydrogen storage systems are however not found.

Liquid hydrogen storage vessels are operated at temperatures around –253 °C (internally) to maintain the liquid form. Pressure will increase when hydrogen evaporates over time but is usually kept below 20-30 bar /4/. In liquid form, hydrogen has a density of 70 kg/m³ and an energy content of 9.87 GJ_{hhv}/m³. This is significantly higher compared to compressed hydrogen storage, but this does not yet include the size of insulation etc. of the storage vessel itself.

5.1.3 Cryo-compressed

Cryo-compressed storage is a combination of cryogenic (extremely low temperature) and pressurized hydrogen storage. Storage containment systems for cryo-compressed hydrogen are similar to liquid hydrogen but can withstand a higher pressure of a few hundred bars. Cryo-compressed storage systems are still only in prototype and have been researched by e.g. BMW for mobile applications. The US department of energy assessed multiple prototype storage systems for cryo-compressed hydrogen in mobile applications /2/, /10/.

The systems are similarly designed and composed of a super insulated type III pressure vessel. The assessed systems varied in size but did not exceed 0.2 m³ of hydrogen storage volume. For a 151 litre storage system the total weight was 145 kg. The operational temperature was between -253 °C and 27 °C, where hydrogen becomes gaseous at higher temperatures and pressure increases. The maximum pressure was 270 bar /2/, /10/.

Some advantages of storing cryo-compressed hydrogen is that at the start, the storage density is similar to liquid hydrogen and decreases to about 30% at the end. Higher pressures and temperatures can be reached, meaning that hydrogen can be vented at higher temperatures (with respect to liquid hydrogen) increasing storage time and making storage safer during dormant periods. However, hydrogen still needs to be liquefied which is costly and has a high energy demand /11/.

Containment systems for cryo-compressed hydrogen still need development and will probably not be applied in the inland shipping industry and therefore not further considered in this study.

5.2 Material based storage

5.2.1 LOHC

LOHC is a diesel like substance and can easily be stored in conventional steel tanks. Therefore, practically all current storage systems for diesel or other oil like substances can be used for storage of LOHC /17/. This means that existing infrastructure such as bunker ships, semi-trailers or ISO containers fitted with a steel tank can be used.

For transport of LOHC, only one tank containing either LOHC⁻ or LOHC⁺ is needed. When LOHC is to be used on-board however, LOHC⁻ and LOHC⁺ should be stored separately as LOHC is dehydrogenated when used. To limit additional on-board space requirements for dehydrogenated LOHC three storage system configurations are identified and are depicted in Figure 10.

1. Two separate tanks with the same volume. LOHC⁻ is stored in the second container.
2. Multiple smaller tanks. When one LCOH⁺ tank is empty, it can be used to store LOHC⁻.
3. One single tank with a membrane separating the LCOH⁺ and LCOH⁻ (volume exchange tank).

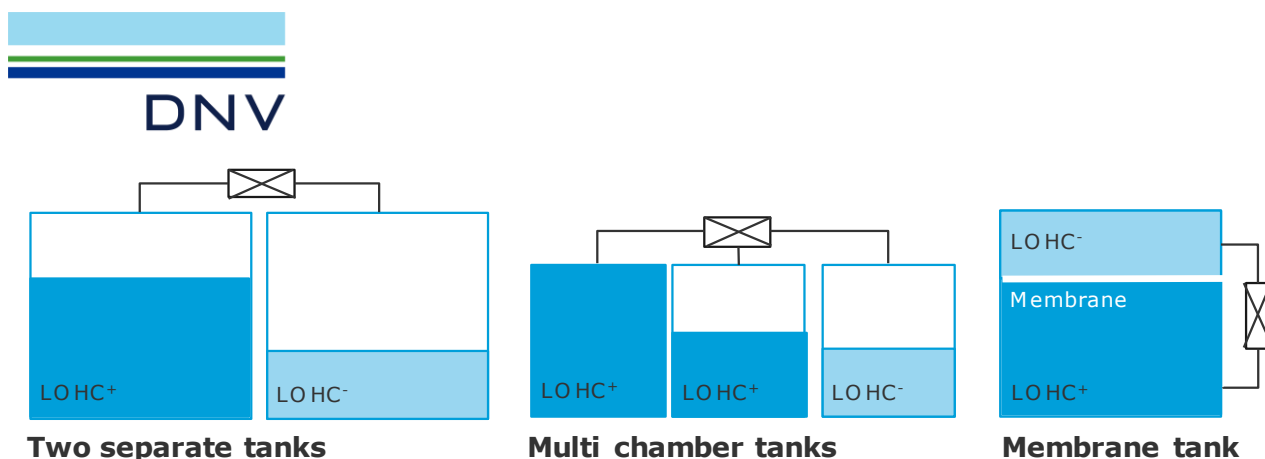


Figure 10: Possible system configurations for on-board LOHC storage.

LOHC can be stored at ambient pressure and temperature and can be stored for long periods without any losses. It can be classified as a non-dangerous good and is difficult to ignite /4/. The storage capacity of hydrogen in LOHC is 6.23 wt%, 57 kg of H₂ per m³ LOHC (8 GJ_{h_{th}}/m³). This is in between compressed and liquid hydrogen storage but this does not yet include the storage system and possible release systems (if ammonia will be converted to hydrogen).

A company called Hydrogenious has been interviewed and is offering commercial LOHC storage and release systems for stationary(onshore) applications. In their product sheets multiple storage systems are included which can be stored stationary or swapped. The figure below gives an overview. They also offer hydrogen release systems and are fitted in standard ISO containers ranging from 20 ft. to 40 ft. The 40 ft. system is capable of releasing 22.5 kg of H₂ per hour, which is purified, pressurized and can be directly fed into a fuel cell. Their systems are now only available for stationary applications, but they are currently developing mobile systems for on-board applications. They expect a prototype in the coming years.



Figure 11: Examples of Hydrogenious storage systems /18/.

Some mayor disadvantages of storing hydrogen in LOHC is the need for hydrogen cleaning after dehydrogenation but the most challenging disadvantage is the high temperature, and therefore energy, requirement for hydrogenation and dehydrogenation. The energy requirement is about 50% of its own energy content /17/.

5.2.2 Methanol

Like LOHC, methanol (CH₃OH) is similar to diesel and can be stored under the same conditions. Some examples for storage are; ISO tank-containers for mobile transport, semi-trailers, large steel tanks or for bulk storage (e.g. in port); tank farms with fixed/floating roof tanks /23/.

On-board use of methanol as a fuel will result in a waste stream of carbon dioxide (CO₂), which should be captured and stored to avoid carbon emissions. Methanol can be used directly in a combustion engine, in a direct methanol fuel cell,

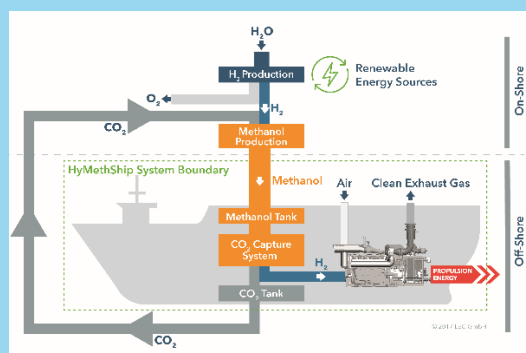
or can be reformed to produce hydrogen. In any case, CO₂ should be stored on board, which results in an additional storage system. The storage of CO₂ can be either in pressurized form or liquid. CO₂ is transported, stored and handled in liquid form, either at ambient temperature (in cylinders or not insulated storage tanks at a pressure of 45 - 65 bar) or refrigerated (in transportable vessels and storage tanks) at a temperature range of -35 °C to -15 °C and a pressure of 12 to 25 bar. /24/

Methanol has a higher heating value of 22.7 MJ/kg and a density of 792 kg/m³ (normal conditions) /24/. If it were to be burned directly in a combustion engine the storage potential of methanol would be equal to the energy content, 17.9 GJ_{hhv}/m³. As a storage medium for hydrogen, methanol holds 12.5%_{wt} of hydrogen, 99 kg H₂ per m³ of methanol (14 GJ_{hhv}/m³).

PROJECT EXAMPLE

HyMethShip Ferry

Fuel type	Methanol
Storage system:	Carbon steel tanks
Placement:	Below deck
Storage capacity:	Unknown
Pressure:	Atmospheric
Temperature:	Ambient
Additions:	Methanol reformer Hydrogen buffer Liquid CO ₂ storage



Information based on interviews with LEC

5.2.3 Sodium borohydride

Storage of NaBH₄ is fairly simple and similar to that of salt. Exposure to air or moist should be avoided and if those conditions are met an unlimited shelf life is theoretically possible /20/. Storage containers can be found in many shapes, sizes and materials as long as the earlier mentioned preconditions are met. Alternatively, NaBH₄ can also be dissolved in water to allow for pumping, instead of mechanically loading. A stabilizer should then be added to prevent the dehydrogenation reaction between the NaBH₄ and water. This liquid form can be stored in systems for corrosive liquids (one project, H2SHIPS, uses IBC containers).

1 kg of NaBH₄ stores approximately 10.8 %wt (108 g) of hydrogen and when released another 108 g of hydrogen comes from the added water. The density of NaBH₄ is 1070 kg/m³ but as it is stored in a powder/crystals and there are voids between the NaBH₂ crystals, bulk density is 400-500 kg/m³ /20/. For the storage of hydrogen, 12-15 GJ_{hhv}/m³ can be stored in crystal form (calculations based on molar balance). In liquid form, NaBH₄ is dissolved in (pure) water with a stabilizer to prevent dehydrogenation.

In an interview H2 Fuel Systems indicated a NaBH₄ percentage of 25%_{wt} in water capable of storing 200 kg H₂ per m³ of liquid fuel (28.4 GJ_{hhv}/m³). In one of their pilot projects liquid fuel is stored in plastic IBC containers.

If used on-board as a fuel a dehydrogenation system is also required which would be similar in size to a diesel engine (H2 Fuel Systems). In addition pure water is needed for the dehydrogenation process which should be produced on board (from river/sea water) or should be kept in an additional tank /21/.

Use of NaBH₄ on board furthermore requires storage of spent fuel (NaBO₂). This requires additional (double) storage space and adds weight. Here smart solutions like multi chamber tanks or volume exchange tanks could optimize the storage requirements (further discussed under LOHC and shown in Figure 10).

PROJECT EXAMPLE

H2SHIPS Port vessel

Fuel type	Sodium borohydride Dissolved in water
Storage system:	2x IBC tanks
Placement:	Above deck
Storage capacity:	300-350 kg
Pressure:	Atmospheric
Temperature:	Ambient
Additions:	H ₂ extraction system Spent fuel storage



Information based on interviews with the Port of Amsterdam and H2 Fuel Systems

5.2.4 Ammonia

Liquid ammonia is relatively safe in terms of flammability (difficult to ignite) but is highly toxic and storage should meet specific regulations. In the Netherlands this is described in the PGS 12 /15/.

Ammonia can be stored in steel vessels under pressure or refrigerated, where some degree of insulation is applied. Tanks can be found in many shapes and sizes and some are described below.

Semi-trailers For smaller scale applications, such as road transport, cylindrical ammonia tanks (semi-trailers) are found in the order of 50 m³ of transport capacity with a maximum operating pressure of 26-29 bar and a temperature range between -40 and 50 °C /13/.

ISO- tank-containers (T50) It is also possible to fit a cylindrical storage tank in a standard ISO container, capable of storing ammonia under similar conditions as a semi-trailer (22 m³ ammonia in a 20 ft. container) /14/.

Cargo vessel Ammonia in cargo vessels would be stored in large cylindrical and (semi) refrigerated vessels but can also be stored in prismatic shaped vessels for larger quantities, similar to bulk carriers. Ammonia can be transported in type A tanks; flat walled tanks suitable for low temperatures and low pressure. For transport of ammonia, these vessels are operated at ambient pressure and temperatures as low as -48 °C /16/.

On-board use of ammonia is possible by either extracting hydrogen from the ammonia or the direct use of ammonia. For hydrogen extraction, a cracker is needed on-board with additional cleaning and purifying equipment for use in a fuel cell. Alternatively, direct combustion of ammonia or ammonia hydrogen mixtures is currently researched but is not market ready. Direct ammonia fuel cells are also developed but this is still in an early stage.

The advantage of ammonia storage is its high storage density and relatively modest storage conditions (pressure and temperature). Ammonia has a hydrogen content of 17.7 wt% and a density of 674 kg/m³ (at -33 °C) /1/. This results in a storage density for hydrogen of 119.3 kg/m³, 16.8 GJ_{h_hv}/m³. This is significantly higher than liquid hydrogen.

Furthermore, ammonia storage is a proven technology and the bulk supply chain is already in place at large scale. However, ammonia is highly toxic and could prove a serious safety & environmental concern, especially on inland waterways. Another disadvantage is the need for extracting and purifying hydrogen when used in a fuel cell /11//12/.

5.3 Overview & Discussion

The storage methods and containment systems described in the previous sections are discussed in this section with specific focus on application in the inland shipping industry. For each hydrogen storage method, the possible containment systems, pressure, temperature and state of aggregation are provided and summarized in the table below. A comparison is made where the advantages/disadvantages are discussed.

Table 2: Overview of possible storage methods, containment systems (and physical parameters) for use in IWT

Storage method	Containment system	Pressure	Temperature	State of aggregation
<u>Physical-based</u>				
Pressurized	Pressure cylinders/tubes (type I,II,III & IV) placed in cylinder racks, or 20/40 ft ISO tube- or cylinder-containers.	200-1,000 bar	Ambient	Gas
Liquid	Super insulated tanks (IMO type C). Fixed tanks or ISO tank-containers	Atmospheric – 5 barg	-245 to -250 °C	Liquid
<u>Material-based</u>				
LOHC	Tanks similar to diesel tanks; IBC, ISO tank-containers, fixed carbon steel tanks	Atmospheric	Ambient	Liquid
Methanol	1. Tanks similar to diesel tanks; IBC, ISO tank-containers, fixed carbon steel tanks	1. Atmospheric	1. Ambient	1. Liquid
	2. CO ₂ tanks	2. 12-25 bar	2. -35 °C to -15 °C	2. Liquid
Sodium borohydride (NaBH₄)	Crystal: Storage similar to salt (plastic containers) Liquid: Plastic containers, IBC tanks, storage for corrosive liquids	Atmospheric	Ambient	Solid (crystal) Liquid (dissolved in water)
Ammonia	3. Insulated tanks	1. Atmospheric	1. -34 °C	1. Liquid
	4. Insulated pressure tanks	2. 10-30 bar	2. Ambient	2. gas

A clear distinction is visible between physical-based and material-based storage when considering the storage conditions. Pressurized and liquid hydrogen are stored under extremely high pressures or extremely low temperatures. Although containment systems for the material-based hydrogen storage require less “extreme” conditions, their application for inland shipping is still less developed. Especially pressurized storage systems are most developed for mobile applications like inland vessels. Most hydrogen vessels, currently developed, consider pressurized hydrogen, based on an inventarization of current hydrogen projects in the shipping industry (described in Sub-Activity report 1.1b /27/). Pressurized storage also comes with the availability of fixed and swappable systems. Swappable systems could come in containerized solutions (ISO frames), which are already familiar in the shipping industry.

Discussion is still ongoing whether fixed or swappable pressurized hydrogen systems should be applied. Fixed systems have advantages regarding weight and ultimately costs. A fixed system does not need as much protection and safety precautions for transportation as a swappable container would require. Furthermore, for swappable applications a certain number of filled containers should be on reserve to assure security of supply, increasing the need for capital and storage space. A disadvantage of fixed systems however is the need for new bunkering infrastructure and there is still uncertainty of bunkering rates. Swappable containers on the other hand could be exchanged in (already existing) container terminals within a short time. A deeper analysis of the feasibility in IWT is provided in Sub-Activity report 1.1b /27/.

Pressurized hydrogen (fixed or swappable) will most likely be the first (short term) step for applying hydrogen in the inland shipping industry due to the state of development. Material-based storage technologies could be the next step as there are clear advantages regarding storage density. Sodium borohydride, methanol and ammonia have the highest volumetric densities although still a factor 1.5-3 lower than diesel. The figure below gives an overview of the different storage methods including the containment systems.

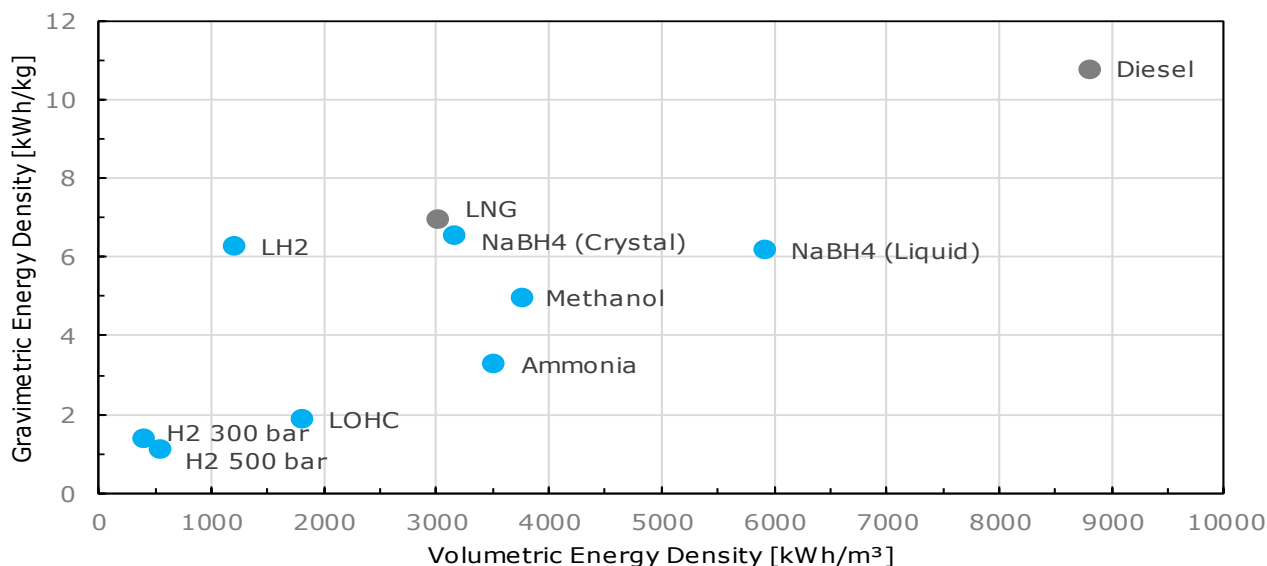


Figure 12: Energy density of hydrogen in different forms incl. storage system

While ammonia is highly toxic, methanol, LOHC and sodium borohydride have a similar or even lower environmental impact when leaking compared to diesel. Methanol, LOHC and sodium Borohydride are also fairly easy to store and methanol and LOHC could even be stored in existing diesel tanks. The difference of energy density should be taken into account but this advantageous when retrofitting existing vessels.

Although containment systems for material-based storage are already developed, the application in the inland shipping sector is new. Furthermore, most material-based hydrogen storage technologies require additional process equipment to extract hydrogen from the carrier material. The development of this equipment for on-board applications is still under development but will also require additional space on board. For example, a methanol cracker to extract hydrogen from methanol is still under development for the scale and (mobile) application of inland vessels. Moreover, these hydrogen extraction processes require energy or will induce losses. More hydrogen needs to be carried on-board to account for this. And lastly, most of the material-based technologies require storage for spent fuel which requires additional space on board.

6 CONCLUSION

In this study possible hydrogen containment systems for transport and propulsion on board of inland navigational vessels are identified. Hydrogen storage methods are sub-divided in physical-based storage (pressurized / liquid) and material-based storage (sodium borohydride, ammonia, LOHC etc.). Containment systems are identified for each storage method and storage conditions (pressure, temperature, physical state and storage density). An overview is provided below.

Table 3: Overview of possible hydrogen storage methods, containment systems and physical parameters for use in IWT.

Storage method	Containment system	Pressure	Temperature	State of aggregation
<u>Physical-based</u>				
Pressurized	Pressure cylinders/tubes (type I,II,III & IV) placed in cylinder racks, or 20/40 ft ISO tube- or cylinder-containers.	200-1,000 bar	Ambient	Gas
Liquid	Super insulated tanks (IMO type C). Fixed tanks or ISO tank-containers	Atmospheric – 5 barg	-245 to -250 °C	Liquid
<u>Material-based</u>				
LOHC	Tanks similar to diesel tanks; IBC, ISO tank-containers, fixed carbon steel tanks	Atmospheric	Ambient	Liquid
Methanol	1. Tanks similar to diesel tanks; IBC, ISO tank-containers, fixed carbon steel tanks	1. Atmospheric	1. Ambient	1. Liquid
	2. CO ₂ tanks	2. 12-25 bar	2. -35 °C to -15 °C	2. Liquid
Sodium borohydride (NaBH₄)	Crystal: Storage similar to salt (plastic containers) Liquid: Plastic containers, IBC tanks, storage for corrosive liquids	Atmospheric	Ambient	Solid (crystal) Liquid (dissolved in water)
Ammonia	5. Insulated tanks	1. Atmospheric	1. -34 °C	1. Liquid
	6. Insulated pressure tanks	2. 10-30 bar	2. Ambient	2. gas

Pressurized hydrogen

Pressurized hydrogen storage is currently furthest developed for mobile applications and is the most applied method in current hydrogen vessel projects. The technical maturity and availability of pressurized hydrogen are clear advantages over other storage methods. The required weight of the containment system, the relatively low volumetric energy density and therefore the space required to store sizable amounts of hydrogen on-board inland navigation vessels are however disadvantages.

Both fixed and swappable systems could be applied in the coming years at storage pressures of 200-500 bar. For the application of fixed systems further analysis is necessary into the bunkering scenarios to assess the bunkering rate as slow bunkering rates could be a disadvantage. Swappable systems can be found in containerized solutions (20/40 ft. ISO containers) or cylinder racks. Swappable systems could be pre-filled, omitting potential delays of bunkering rates, and can be exchanged at a container terminal.

Liquid hydrogen

Infrastructure and containment systems specifically for inland shipping still need further development but there are some pilot projects. The storage density is slightly improved compared to pressurized hydrogen and requires less space and weight. The availability and liquefaction costs are however strong disadvantages. Furthermore, storage of liquid hydrogen on-board generates boil-off gasses, requiring a more frequent and continuous fuel consumption to prevent losses. Liquid hydrogen could be an option as a mid-term solution when liquefaction plants are built and the fuel price comes down.

Material-based storage

There are many advantages for material-based storage such as high storage densities, relatively safe handling (comparable to diesel or even better, except for ammonia) and possible re-use of existing diesel storage and infrastructure. Methanol and LOHC are stored in the same containment systems as diesel, which could potentially be a big advantage when refitting existing inland vessels. A drawback is that some material-based fuels (e.g. LOHC, NaBH_4) require a return cycle meaning that additional containment systems are needed to store the spent fuel on board (taking up space). The application of these technologies and especially the required additional equipment (hydrogen release systems) are however not yet developed for the inland shipping industry or mobility in general and will most likely not be available on a large scale in the next 5-10 years.

Hydrogen bunkering

The feasibility of hydrogen containment systems for use in IWT are closely linked to the possible bunkering scenarios. Sub-Activity report 1.1b /27/ will further focus on bunkering scenarios and identification of feasible options for storing and bunkering hydrogen on-board of inland navigation vessels.

7 REFERENCES

- /1/ D. Durbin and C. Malardier-Jugroot, "Review of Hydrogen Storage Techniques for Onboard Vehicle Applications", Elsevier, 2013
- /2/ R. Ahlialia et al., "Technical Assessment of Cryo-compressed Hydrogen Storage Tank Systems for Automotive Applications", Elsevier, 2010
- /3/ TU Delft, "Hydrogen as the key to a sustainable shipping sector"
<https://www.tudelft.nl/en/3me/research/check-out-our-science/hydrogen-as-the-key-to-a-sustainable-shipping-sector/> visited 31-07-2020
- /4/ D. Stolten and B. Emonts, "hydrogen Science and Engineering" – vol.2, 2016
- /5/ H. Barthelemy, M. Weber, F. Barbier, "Hydrogen Storage: Recent Improvements and Industrial Perspectives", 2016
- /6/ MSC, "Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk", 2016
<http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Maritime-Safety-Committee-%28MSC%29/Documents/MSC.420%2897%29.pdf>
- /7/ M. Bøhlerengen. "Workshop on Liquid Hydrogen Safety", 2019
https://www.sintef.no/globalassets/sintef-industri/arrangement/hydrogen-safety-2019/13_liquid-hydrogen-bunker-vessel_m_bohlerengen_moss_maritime.pdf/
- /8/ Air Products, "Liquid hydrogen – Safetygram 9"
<https://www.airproducts.com/~media/Files/PDF/company/safetygram-9.pdf>
- /9/ NCE Maritime CleanTech, "Norwegian Future Value Chains for Liquid Hydrogen", 2016
<https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf>
- /10/ T. Brunner, "BMW Hydrogen – Hydrogen Storage Workshop", 2011
https://www.energy.gov/sites/prod/files/2014/03/f12/compressed_hydrogen2011_7_brunner.pdf
- /11/ B. Sundén, "Hydrogen" Chapter 3 in "Batteries and Fuel Cells", 2019
- /12/ E. Krystina et al., "Ammonia for Hydrogen Storage; A Review of Catalytic Ammonia Decomposition and Hydrogen Separation and Purification", 2019
- /13/ Cryocan, Ammonia Semi Trailer, <http://cryocan.com/en/chemical/ammonia-semi-trailers/> visited on 05-08-2020
- /14/ Linde Group, Datasheet: Ammonia, NH₃, https://www.linde-gas.com/en/images/linde-datasheet-01-ammonia-June-2017_tcm17-417364.pdf visited on 05-08-2020
- /15/ PGS 12: Ammoniakopslag en verlading, 2020
https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS12/Concept_interim_PGS_12_v0.2_april_2020.pdf
- /16/ Liquefied gas carrier, Fully refrigerated tankers that carry LPG, Ammonia & Vinyl chloride,
<http://www.liquefiedgascarrier.com/Fully-Refrigerated-Ships.html> visited at 05-08-2020
- /17/ Marigreen, "Perspectives for the Use of Hydrogen as Fuel in Inland Shipping", 2018

- /18/ Hydrogenious, Product sheet: Hydrogen Infrastructure Solutions, [https://www.hydrogenious.net/wp-content/uploads/2018/08/Hydrogenious Technologies_LOHC_Products.pdf](https://www.hydrogenious.net/wp-content/uploads/2018/08/Hydrogenious_Technologies_LOHC_Products.pdf) visited at 06-08-2020.
- /19/ TU Delft, “Maritime application of sodium borohydride as an energy carrier”, 2019.
- /20/ Carl Roth, Veiligheidsinformatieblad, overeenkomstig Verordening (EG) Nr. 1907/2006 (REACH), Herziening 28-05-2020, <https://www.carlroth.com/medias/SDB-4051-BE-NL.pdf?context=bWFzdGVyfHNIY3VyaXR5RGF0YXNoZWV0c3wyOTYzODd8YXBwbGljYXRpb24vcGRmfHNlY3VyaXR5RGF0YXNoZWV0cy9oNzcvaGRkLzg5ODY1MDQzNjQwNjIucGRmfDMxZmM4MWE0NzE4ZDc4Nzg0YzJhZWY0YWJiZTZjZjU5MTFhZTMxMTM0ZTVlMDI2Y2RiZTQ5NmlwMTA0MzViM2E>
- /21/ H2 Fuel Systems website, Working principle, <https://h2-fuel.nl/werking-van-h2fuel/> visited on 21-09-2020.
- /22/ DNV, “Assessment of selected alternative fuels and technologies”, 2018
- /23/ Methanol Institute, “Methanol Safe Handling Manual”, 2008
- /24/ EIGA, “Refrigerated CO₂ Storage at Users’ Premises”, 2008
- /25/ EICB, “Waterstof in Binnenvaart en Short Sea”, 2020
- /26/ Baetcke and M. Kaltschmitt, “Hydrogen Supply Chains, Chapter 5 - Hydrogen Storage for Mobile Application: Technologies and Their Assessment”, 2018
- /27/ DNV, RH2INE Sub-study 1a, Sub-activity 1.1b: “Hydrogen Bunkering Scenarios”, March 2021
- /28/ HyNed, HyMove, HAN and KIWA, “Hydrogen and hydrogen carriers for inland shipping – Strategic program to realize hydrogen based inland shipping supply chains – Report of phase 1: Feasibility study”, 2020



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