RH2INE PROGRAM: SUB-STUDY 1A: SAFETY FRAMEWORK CONDITIONS

SuAc 1.1b Hydrogen Bunkering Scenarios

RH2INE Consortium

Report No.: 10247894-2, Rev. 1
Document No.: 11I1RCRW-2
Date: 2021-03-24

Project name: RH2INE program: sub-study 1a: Safety framework conditions

Report title: SuAc 1.1b Hydrogen Bunkering Scenarios

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Date of issue: 2021-03-24

Project No.: 10247894

Organisation unit: Risk Management Advisory Rotterdam

Report No.: 10247894-2, Rev. 1

Document No.: 11I1RCRW-2

Applicable contract(s) governing the provision of this Report:

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Objective: this report provides an overview of possible ways to bunker hydrogen to inland navigational vessels and the most feasible bunkering scenarios are identified in a workshop with the RH2INE consortium participants and stakeholders.

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Keywords:
Hydrogen, Bunkering, Inland Waterway Transport

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2021-01-23	Draft report	D. van der Meulen	J. Douma	R. van der Spek
1	2021-03-24	Final report: minor textual changes & conversion to new DNV template	D. van der Meulen	J. Douma	R. van der Spek

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ABREVIATIONS

CO_2	Carbon Dioxide
DG	Dangerous Goods
IMO	International Marine Organization
IWT	Inland Waterway Transport
LH_2	Liquid Hydrogen
LNG	Liquid Natural gas
LOHC	Liquid Organic Hydrogen Carrier
$NaBH_4$	Sodium borohydride
PoR	Port of Rotterdam
RH2INE	Rhine Hydrogen Integration Network of Excellence
ro-ro	Roll-on/roll-off
SIMOPS	Simultaneous Operations
STS	Ship-to-Ship
TPS	Terminal-to-ship via pipeline
TTS	Truck-to-Ship

EXECUTIVE SUMMARY

Introduction

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). This report is the result of “sub-activity 1.1b: Identification of hydrogen bunkering scenarios for 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.

This sub-activity report provides an overview of the possible ways to bunker hydrogen to inland navigational vessels including relevant bunker parameters (e.g. bunker rates).

Included in the report is a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium. This report provides input to RH2INE Sub-study 1b (Safety and regulatory analysis) and Sub-study 1d (Location study).

Objective

The objective of this study is to identify feasible hydrogen bunkering scenarios for inland navigational vessels. The scenarios are described and characterized, which includes a preliminary assessment of advantages and disadvantages.

Approach

As a starting point a literature review was conducted to identify the possible bunkering configurations and hydrogen bunkering scenarios. Information about general bunkering configurations, physical parameters (e.g. bunker rates) and the advantages and disadvantages of the hydrogen bunkering scenarios 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 and by conducting interviews with project initiators of hydrogen pilot vessels.

The preliminary results were discussed during a workshop with the RH2INE consortium participants and stakeholders. The most feasible hydrogen bunkering scenarios were identified for the short-term (1-5 years), mid-term (5-10 years) and long-term (10-20 years).

Results & Conclusions

In general, bunkering can take place via four different configurations: truck-to-ship, ship-to-ship, bunker stations and swapping of tank-containers. The applicability of each configuration and the method of bunkering depends on the physical state in which hydrogen (pressurized, liquid or hydrogen carrier) is stored on board inland navigational vessels. The bunkering scenarios as determined in the workshop are given below with the main reasons why they are selected.

Short-term (1-5 years): swapping tube-containers with pressurized hydrogen at container terminals

The most feasible scenario for the short-term is swapping pressurized hydrogen in swappable containerized containment systems (tube-containers) at container terminals. There are clear advantages compared to bunkering to fixed tanks on board due to the following reasons (based on discussions held during the workshop):

- Shorter bunkering times. With fixed tanks the bunkering times are currently longer due to limitations in bunker rates (especially relevant for cargo/container vessels that have a higher consumption/demand)1. The conventional operational process of bunkering is eliminated;
- Swappable tanks are in particular suitable for cargo vessels such as container vessels (easy handling) but can also be feasible for bulk/tanker vessels and push boats (in terms of required space). Hoisting above of these vessels at container terminals is more challenging, but still considered feasible;
- The use of swappable tanks seems to be cheaper in the long run compared to fixed tanks. The supply chain is better (no new infrastructure required) and there is better availability (transport of containers per road/train/vessel). However, it requires preparation of the logistical process and more frequent bunkering might be required resulting in additional stops;
- Swappable systems allow for modularity and flexibility. The market can still select the best option for the storage system in the future when the market is more mature. For example, adapted systems can be optimized to allow for fixed tanks with liquid hydrogen or hydrogen carriers in the future.

Pressurized hydrogen has advantages over liquid hydrogen and hydrogen carriers because the fuel and the technology (containment systems) is commercially available. Therefore, only use of pressurized hydrogen is considered to be feasible in the short-term. The low energy density is not considered as a showstopper although more frequent bunkering would be required compared to conventional bunkering of diesel. Bunkering of gaseous hydrogen via hose to fixed tanks on board is not excluded as feasible scenario and could be a good option for smaller (short distance) inland vessels with a low consumption (e.g. ferries, cabin vessels) and that are moored for a longer period time (e.g. overnight) when bunkering can take place. Swappable cylinder racks, however, would be the fastest bunkering option for ro-ro ferries.

Mid-term scenario (5-10 years): bunkering of liquid hydrogen

At the moment pressurized hydrogen is more cost-efficient for inland vessels compared to liquid hydrogen. The high fuel price of liquid hydrogen is expected to improve significantly when first liquefaction plants are built. Rules & regulations are currently not in place for bunkering liquid hydrogen. Requirements for bunkering in (port) regulations and inland waterway legislation first needs to be developed (therefore the short-term solution is pressurized hydrogen). However, liquid hydrogen has a better energy density than compressed hydrogen. Bunkering of liquid hydrogen is similar to bunkering of LNG. In principle, existing technology for LNG can be modified and adapted to liquid hydrogen after extensive engineering and testing before solutions become commercially available. For these reasons liquid hydrogen is still considered as a feasible mid-term scenario for IWT.

Bunkering of liquid hydrogen to inland vessels will probably start with truck-to-ship (limited infrastructure is required). When the market is more mature, bunker barges and/or bunker stations could be developed. The continuous generation of boil-off gas is not considered as an issue due to the good tank insulation, long holding times and frequent consumption.

Long-term scenarios (10-20 year): bunkering of hydrogen carriers

Bunkering of hydrogen carriers is considered to be a long-term scenario for inland shipping mainly because the technologies are still immature and complex systems are required. sodium borohydride seems the most promising in terms of energy density and safety, but the required technology is still at an early stage of development.

LOHC and methanol are promising in terms of safety, availability & existing supply logistics. In addition, potential re-use of existing diesel storage and infrastructure is an advantage. 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 both LOHC and methanol require a return cycle and complex systems on board, which may be too challenging for the

[1] However, it must be mentioned that there is still uncertainty with respect to the maximum feasible (safe) transfer rate that can be achieved with bunkering gaseous hydrogen to inland vessels. It seems that also high bunker rates are possible reducing the bunkering time significantly in comparison with values reported in literature (see paragraph 5.1.3 & chapter 7 for more information).

inland shipping sector. Nonetheless, it must be noted that ship-to-ship bunkering of a seagoing vessel with methanol is foreseen to take place in 2021. Furthermore, there are currently many ongoing promising developments in China regarding the use of LOHC in inland shipping, which may accelerate the adoption of the fuel.

A more in-depth discussion about some issues and relevant points found in literature and raised during the workshop and interviews regarding the identified bunkering scenarios is included in chapter 7. These may require further attention or additional research.

As a final note, it is clear that swapping of containers have apparent advantages over the other configurations and bunkering scenarios especially in the short-term. However, this would imply adopting a completely different approach towards bunkering in comparison to how conventional bunkering of diesel takes place today.

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 specific report focusses on sub-activity 1.1b: *Identification of hydrogen bunkering scenarios for inland navigational vessels*. In this sub-activity report, an overview of the possible ways to bunker hydrogen to inland navigational vessels is provided including relevant bunker parameters (e.g. bunker rates).

Included in the report is a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium participants and stakeholders. This report provides input to RH2INE sub-study 1b (Safety and regulatory analysis) and sub-study 1d (Location study).

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2 STUDY APPROACH

The approach for the study 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. Interviews with project initiators;
5. Identification, characterization of bunkering scenarios and preliminary assessment of advantages and disadvantages;
6. Identification of the most feasible hydrogen bunkering scenarios in a workshop with RH2INE participants and stakeholders.

These steps are described below. The first four steps are the same as in the approach for sub-activity report 1.1a: hydrogen containment systems /1/.

Literature review

Various studies have been conducted related to the feasibility of hydrogen (bunkering) for IWT. The most relevant studies are:

- EICB, "Waterstof in Binnenvaart en Short Sea", 2020 /2/
- DUAL Ports, "Feasibility of Hydrogen Bunkering", 2019 /3/
- Marigreen, "Perspectives for the Use of Hydrogen as Fuel in Inland Shipping", 2018 /4/
- HyNed, HyMove, HAN and KIWA, "Hydrogen and hydrogen carriers for inland shipping, 2020 /5/

The EICB study was also used as a starting point for identifying current hydrogen projects in the shipping industry.

Review of DNV reports and projects

Other DNV projects and those involved were consulted for their insights in bunkering of hydrogen. This allowed for the addition of practical knowledge in the report about e.g. typical bunker rates 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 and 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 identify and characterize the different hydrogen bunkering scenarios, current applications and the overall feasibility in inland shipping. Specific technical information about bunkering (e.g. bunkering rates, duration, pressures etc.) was collected based on DNV involvement in hydrogen programs and projects in the months after the workshop and subsequently incorporated in this report.

Interviews with project initiators

Finally, all project initiators of identified hydrogen projects in the shipping industry were contacted for technical project details about bunkering of hydrogen and to give their insight in applying hydrogen in the inland shipping industry. In total 12 parties were interviewed:

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

An overview of the current applications and identified projects is given chapter 3. The relevant insights gained during the interviews are summarized and further discussed in the discussion (chapter 7).

Identification, characterization of bunkering scenarios and preliminary assessment of advantages and disadvantages

Based on the collected information in the previous steps, the bunkering scenarios can be identified and characterized. First, a detailed description of general bunkering configurations (e.g. truck-to-ship, ship-to-ship, bunker stations etc.) is provided in chapter 4. The typical aspects, advantages and disadvantages and the potential application for IWT are discussed per configuration.

The applicability of each configuration and method of bunkering depends on the physical state in which hydrogen (pressurized, liquid, hydrogen carrier) is stored on board. For this reason, a more detailed characterization (including typical bunker rates etc.) is included in chapter 5, which will focus specifically on hydrogen bunkering scenarios. This includes a preliminary assessment of the advantages and disadvantages of the identified configurations and scenarios, which is further discussed in a workshop.

Identification of the most feasible hydrogen bunkering scenarios in a workshop with RH2INE participants and stakeholders

A workshop with RH2INE participants and stakeholders was organized to discuss the feasibility of the identified hydrogen bunkering scenarios. The workshop was held at the 30th of October with the goal to identify the most feasible hydrogen bunkering scenarios for inland shipping in the short-term (1-5 years), mid-term (5-10 years) and long-term (10-20 years). The structure and main outcomes of the workshop are provided in chapter 6. Relevant points and issues raised during the workshop about the scenarios are discussed in chapter 7.

3 CURRENT APPLICATIONS AND PROJECT DEVELOPMENT

Insight in the current application of hydrogen on-board of ships was obtained through identifying current (pilot) projects. The projects were identified through desk research, DNV's own projects and insights and interviews with project initiators.

A first overview of hydrogen vessel projects was based on the already comprehensive list provided in the EICB report /2/. DNV added their own projects, projects found in other literature and added technical details through desk research or contacted the project initiators. In total, 73 projects were identified for which DNV tried to obtain the following information:

- Ship type — e.g. ferry, container vessel, tug/push boat
- Region
- Inland or seagoing vessel
- Commissioning date
- Fuel type — e.g. compressed H_2, Liquid H_2, ammonia, methanol
- Containment system — e.g. fixed or swappable compressed tank, steel tank
- Placement of tanks — above or below deck
- Storage tank type — e.g. type IV compressed, IMO type C
- Storage pressure
- Storage temperature
- Storage capacity — per tank (if multiple) and total
- Bunkering configuration — e.g. truck-to-ship, bunker station, ship-to-ship, swapping
- Bunkering pressure
- Bunkering temperature
- Bunkering rate
- Transfer system — e.g. crane, hose, arm
- Pump/compressor type
- Additional safety equipment
- Application area — e.g. terminal area, quay side, buoys

Not all information could be completed or was known and only a limited number of project initiators responded to the inquiry. In addition, some of the information was confidential and could therefore not be referred to in this report. However, in some cases it was possible to anonymize the confidential data so that it could be used to characterize the bunkering scenarios.

Based on the identified projects, compressed hydrogen is currently the most applied option of storing hydrogen on-board of both inland and seagoing vessels. A third of the vessels considers compressed hydrogen, another third is unknown and the rest considers Liquid hydrogen (LH_2), methanol, ammonia, sodium borohydride or Liquid Organic Hydrogen Carrier (LOHC). The figure below gives an overview of the applied hydrogen technologies and distinguishes between inland and seagoing vessels.

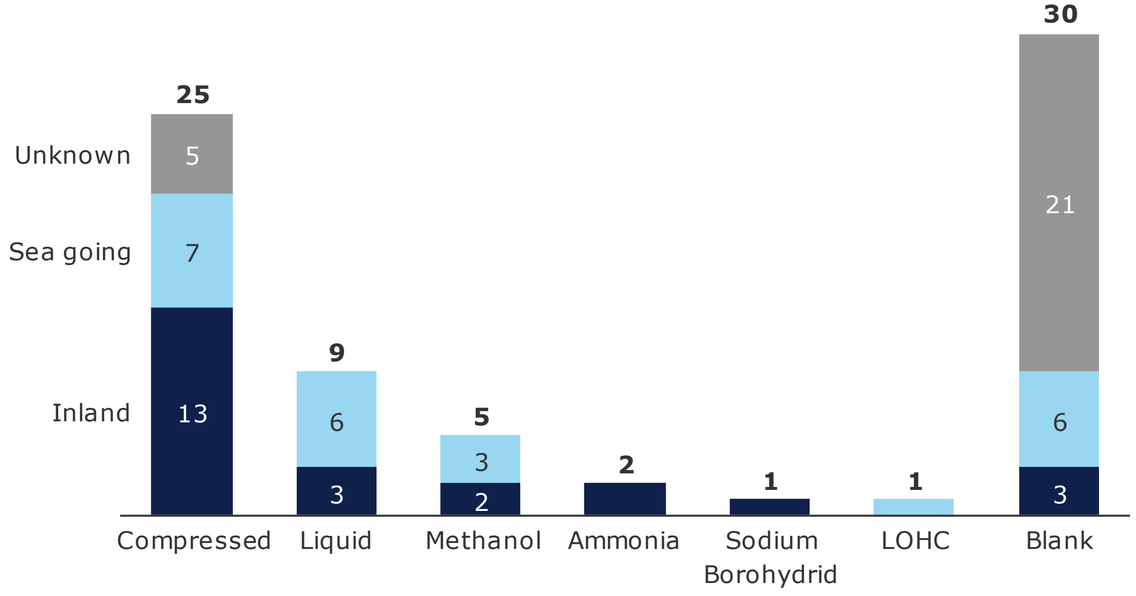

Figure 1: Applied hydrogen technologies on ships for the 73 identified projects.

Most parties consider compressed hydrogen for their projects as this option is currently easier to implement because the technology is commercially available. Liquid (green) hydrogen is poorly available and the required technologies for using hydrides (e.g. ammonia, methanol, etc.) is still in early stages of development. The disadvantages of low volumetric storage densities of compressed hydrogen were still acceptable for most of the interviewed parties.

Both swappable and fixed tanks are considered in the projects with pressurized hydrogen storage but the majority considers fixed tanks. It should also be noted that detailed information on the method of bunkering is still unknown for the majority of the identified projects. Most project initiators were in the first stage of focussing on the technology and requirements for storage on board rather than how to get the hydrogen on board, which would be assessed later in the project.

Parties considering methanol, LOHC and sodium borohydride were included in the interviews. One specific project is the HyMethShip where methanol is cracked on board. A Ferry was selected as a proof of concept as this would limit the number of harbours and the required infrastructure for this pilot project. In addition to a methanol fuelling infrastructure a CO_2 infrastructure is also needed. The concept is still to be further developed.

4 GENERAL BUNKERING CONFIGURATIONS

This chapter describes the general bunkering configurations. The typical aspects, advantages and disadvantages and the potential application for IWT are discussed for each of the identified configurations. Because the method of hydrogen bunkering depends also on the physical state in which hydrogen (pressurized, liquid, hydrogen carrier) is stored on board of inland navigational vessels, a more detailed characterization (including typical bunker rates etc.) is given in chapter 5.

In general, the following main bunkering configurations can be distinguished:

1. Truck-to-ship (TTS);
2. Ship-to-ship (STS);
3. Fixed onshore storage to ship (bunker stations), also called “terminal-to-ship via pipeline” (TPS), but further referred to as bunker stations.
4. The use of mobile hydrogen tanks (swapping of containers).

Configurations 1, 2 and 3 are illustrated in the figure below. The above configurations are detailed in the following paragraphs.

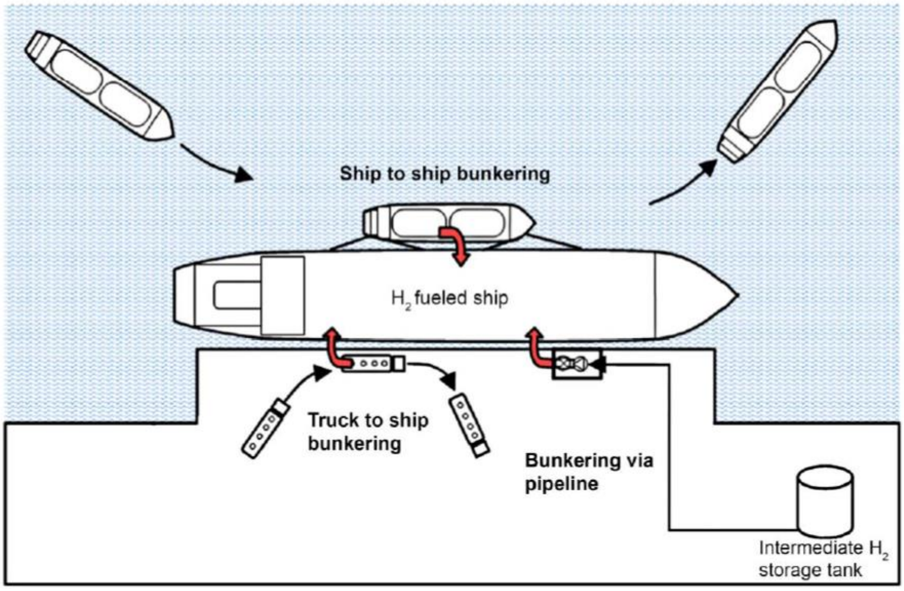

Figure 2: Illustration of different bunkering configurations (source: DNV report ref. /6/)

4.1 Truck-to-ship bunkering (TTS)

Truck-to-ship bunkering is where vessels are directly bunkered by a truck (e.g. tube-trailer with pressurized hydrogen or trailer with a LH2 tank container) positioned on a quay. The bunkering process is straightforward.

Typically, TTS is undertaken by connecting (a) flexible hose(s) to the bunker manifold on the receiving vessel. TTS bunkering generally involves lower bunkering rates as compared to other configurations and is therefore mostly used for vessels with a low fuel tank capacity such as small ferries, inland ships and port vessels. Sometimes multiple trucks are employed that normally bunker in series[2] to meet the bunker demand.

TTS bunkering offers great flexibility to vessel owners and operators; however, capacity and supply security can be limited. For vessels with small storage volume, it can be used as a start-up solution to probe the hydrogen market before

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[2] And in exceptional cases in parallel with means of a manifold in a skid

making a large capital investment in hydrogen bunkering infrastructure. Depending on the type of vessel and related operations, a potential drawback of TTS bunkering is the presence of the truck at the quay, which could restrict cargo and passenger operations during bunkering. The cost per kg of hydrogen is relatively high for this solution, due to high transportation costs.

TTS bunkering has many potential advantages . Portability, low capital investment, and capability to transport hydrogen to remote locations on short notice and on demand (offering flexibility) are the main reasons that TTS bunkering could be attractive.

TTS bunkering is not without its drawbacks. The feasibility of transferring hydrogen truck-to-ship for very large volume transfers is limited by transfer rate and the volume trucks can deliver. TTS bunkering has one of the lowest transfer rates. The rate is driven primarily by the rate at which the receiving vessel can bunker hydrogen, the connecting pipework/hoses, any truck-installed transfer pump (liquid) or compressor (gaseous), and the pressure difference between the supply and fuel tank.

TTS bunkering could be performed in two different ways: directly from the truck to the fuel tank by flexible hoses or indirectly through a fixed connection on shore (pipeline to bunker boom[3] or hose transfer manifold). The transfer can be achieved by a pump/compressor fitted on the truck and a manifold (which may be placed on a floating structure such as a pontoon), by pressure differential or combination of both. The preferred method will also depend on the physical state of hydrogen storage (pressurized, liquid, energy carrier).

TTS bunkering requires a location where the truck(s) could be positioned at a quay, directly next to the vessel that will be bunkered. Possible locations are normally selected by the authorities. Along the Rhine such a location could in principal be located in a port or along the river. Because of safety reasons, the location would need to facilitate safe mooring of the vessel. In principle, the requirements to a location are similar to those of current bunker stations for conventional fuels on the Rhine. On the Upper and Middle Rhine, these bunker stations are mostly seen in ports. On the Lower Rhine, bunker stations are mostly located along the river. The reason of this is the fact that the Upper and Middle Rhine sections are narrow, highly trafficked and with strong currents. In these sections it is difficult to find suitable locations for a bunkering facility along the river. On the Lower Rhine and connected inland waterways the waterways are wider and the currents lower, which allows the safe mooring of vessels along the river.

Similar siting of TTS bunker locations is already adopted in current practice for Liquefied Natural Gas (LNG). The ports of Rotterdam, Antwerp and Amsterdam have indicated dedicated bunker locations, primarily located in port basins. Bunker locations in Mannheim and Zwijndrecht for example, are located along the river.

4.2 Ship-to-ship bunkering (STS)

Ship-to-Ship bunkering is the dominant configuration for conventional bunkering of diesel and is generally seen as the most feasible bunkering solution when larger bunker volumes are required.

STS bunkering is the direct transfer from a bunker barge or vessel, which is moored alongside the hydrogen-fuelled vessel. This would normally be done when the receiving vessel is moored at terminals (e.g. during cargo operations) as this would be most time efficient.

It is a time efficient way of bunkering due to the relatively high bunker rates and the fact that bunkering in principle does not interfere with cargo and passenger operations. Therefore, this operation could be done in parallel which reduces the turnaround time of the vessel. In this case, it should be assessed whether the risk of such Simultaneous Operations (SIMOPs) is acceptable by means of a location specific risk assessment. As such, it is an attractive bunkering mode for vessels requiring large bunker volumes and vessels with short turnaround times.

[3] A bunker boom is a sort of crane that comprises of a flexible pipeline and flexible hose to make the connection with the bunker manifold on the receiving vessel. An example is provided in Figure 4.

STS bunkering is also a flexible solution as it could be conducted in different parts of the port (if not restricted by port regulations) and it could accommodate all volume-ranges.

The bunker barges and vessels will need to be supplied with hydrogen, which ideally requires the presence of an (intermediary) hydrogen production or storage site in or within a certain distance of the port.

The primary disadvantage of this bunker configuration concerns the high costs related to the investment in the vessel, hydrogen supply infrastructure and the operating costs. In addition, STS transfers have additional potential threats (e.g. excess movement between vessels, ship collision) compared to shore-based transfers. These risks can be mitigated if they are identified and addressed in the design and operation.

STS bunkering of inland vessels will be conducted while moored at a quay side. The risk and conditions of sailing STS operations of inland vessels has always been a topic of discussion. The risk of this type of operations is generally considered higher than that of the other bunkering configurations because of the following reasons:

- The likelihood of a mechanical impact due to a nautical incident, such as collision, grounding etc. with the bunker equipment is significantly higher while sailing than while safely moored. The main reasons for the higher likelihood are the vicinity of other ship traffic, weather and current conditions and the fact that the crew will have to split their attention between navigating and the bunker operation;
- In case of an uncontrolled situation, one of the involved ships might drift towards other ship traffic, including passenger vessels, or populated areas near the river causing a risk towards third party population;
- The ships are less accessible for emergency response teams. In addition, the emergency planning involving shore based services (such as the fire brigade) is more complicated.

Because of the above reasons and the lack of experience with bunkering hydrogen in general, sailing STS operations are not foreseen for IWT. Port Bye Laws (of Rotterdam and Antwerp) and bunker checklists for LNG for example, require both ships involved in the STS operation to be securely moored.

As ship-to-ship bunkering is the dominant bunker mode for conventional bunkering of inland vessels on the Rhine Corridor and because of its time efficiency, this would be the preferred bunker mode from the perspective on inland ship operators. However, this bunker configuration is not expected to be widely established for hydrogen in IWT, at least not in the short-term and is especially not suitable for bunkering gaseous hydrogen due to its low energy density and required storage/bunker volumes (further discussed in chapter 5).

4.3 Bunker stations

A third option for hydrogen bunkering is establishing a bunker station, where vessels moor at a jetty or pontoon and are supplied with hydrogen from a storage tank by means of a pipeline. The bunker station can be supplied by ship, truck, train or pipeline. At a bunker station, hydrogen is transferred from a fixed storage tank (usually placed on land) through a cryogenic pipeline with a flexible hose at the end to a vessel moored at a quay, jetty or floating pontoon.

As for STS bunkering, this bunker configuration can accommodate high flow rates resulting in short bunker times, which makes it an attractive solution for vessels requiring larger bunker volumes.

Small-scale bunker stations will normally consist of one storage tank. If capacity needs to be increased, this can be simply achieved by adding more storage tanks. The investment for such an increase of scale is limited and therefore this is a scalable solution which is attractive if demand is uncertain. However, it is less efficient than STS bunkering, as vessels have to travel to the bunker station and cannot conduct cargo and bunkering operations in parallel.

As inland shipping is generally less attached to stringent time schedules than the maritime industry, bunkering from bunker stations comes in as an attractive alternative for purely IWT ports with a significant demand. This option requires significant investment costs, but less than STS bunkering and is scalable in case demand increases.

In case of a terminal facility onshore, the investment costs for constructing the terminal are high compared to those of other configurations. An alternative to an onshore facility requiring smaller investment costs is floating storage, for instance a bunker pontoon. This solution is attractive when space onshore is limited or as a temporarily solution to fulfil short-term demand. As such, it is a flexible solution which could facilitate larger volumes than STS bunkering.

Bunker stations for diesel along the Rhine corridor are typically pontoons. The main advantages of a pontoon are that it does not occupy quay space and that in case of varying water levels, the height difference between vessel and pontoon is always limited. Furthermore, a floating facility is less exposed to flooding and possible resulting damage. Because of these reasons it could be attractive to develop floating bunker stations on the Rhine Corridor. Such a floating installation could be a barge or a retrofitted tanker vessel, which is permanently moored at one location.

The main disadvantage of a floating bunker station is the risk of collisions and the possibility that the installation could sink or capsize. A collision by a passing vessel could lead to a rupture of the storage tank. At this moment, the increased risk of floating storage for application in bunker stations in comparison to onshore bunker stations has not been researched in detail and no common view has been established under which conditions this can be allowed. As an intermediate solution, the storage tanks could be placed on land while hydrogen is delivered to the vessels from a pontoon. However, if a pontoon is used for delivery of the fuel to the ships, attention needs to be paid to the movement of the pontoon. These movements should not damage the equipment. At this moment, no floating hydrogen bunker stations are being operated or developed.

Like for TTS and STS activities, bunker locations could be located both in ports and at riversides, provided that vessels can moor safely.

DNV

4.4 Swappable mobile tank-containers

Swappable mobile tank-containers involve containerised storage, replacing the bulk transfers/handling and removing the need for fixed fuel tanks on board and on shore at e.g. a bunker station. In such a case, the fuel tank is placed on deck or below deck in a special storage hold on the receiving vessel. This solution may offer advantages of simplified distribution at start-up and lower delivered costs as no expensive land-based infrastructure is required. Also, the “bunker” time could be significantly shorter than for the other configurations and the operation could take place at the same location as the (un)loading operations, which makes this solution attractive for vessels utilizing cranes and similar port infrastructure such as container ships. The tank-containers could be handled as standard dangerous goods (DG) containers, for which procedures and regulations are widely established. Alternatively, if the hydrogen fuelled vessel is fitted with an onboard crane, it would (in theory) also be possible to load the tanks directly from another vessel or truck while moored at the quay. This is however generally not considered as the preferred safe solution considering the weight of the containment system (in particular for compressed hydrogen).

For IWT this configuration requires a multimodal infrastructure (i.e. supply is possible via different modes of transport: road, rail, water etc.), which is already available at container terminals but not necessarily at terminals used for other cargoes. Therefore, the most effective solution would be to load the tank-containers at existing container terminals. An advantage of swappable containers is that it offers modularity and flexibility towards future adaptations of technology or adoption of (other) alternative fuels in IWT. The market can still select the best option for the storage system in the future when the market is more mature. For example, adapted systems can be optimized to allow for fixed tanks with liquid hydrogen or hydrogen carriers in the future

A drawback of this configuration is the limited capacity of a swappable tank as compared to a fixed on-board fuel tank and that the tanks would occupy space that cannot be used for cargo. This is particularly applicable for bulk cargo vessels and container vessels. However, as inland vessels will typically need only one or two tanks to fulfil their demand, this is much less of an issue than for seagoing ships and, depending on the lay-out of the vessel, does not necessarily severely restrict the cargo space. For example, for medium-sized inland containerships[4] requiring two fuel tanks of 40 ft, the loss in capacity could be around 2%.

Another drawback includes the need for onshore storage space when the market becomes more mature. A large stock of containers would be required at the container terminal or close to the harbour, increasing the need for capital and storage space, which is already limited in most inland ports.

Although this configuration does not come with the specific bunkering risks during conventional hose transfer, it is not without risk. The mobile tanks could be dropped during loading operations and the frequent connection and disconnection of the vessel’s piping system to the fuel tanks could induce a higher leak frequency.

[4] Inland container vessels have capacity varying from 24 TEU for the smallest to 480 TEU for the largest vessels /7/

It is clear that this configuration could have apparent advantages over the other configurations; however this would imply adopting a significant different approach towards bunkering in comparison to how conventional bunkering of diesel takes place today.

4.5 Comparison

Table 1 summarizes and compares the advantages and drawbacks of each of the four considered configurations, as discussed in the previous paragraphs.

Table 1: Advantages and drawbacks per bunkering configuration

	TTS	STS	Bunker station	Swappable tank-containers
Typical volumes	50 - 100 Nm^3	100 – 1000 Nm^3	All volumes	20 – 40 Nm^3 per tank
Pro's	• Flexible • No infrastructure required: low investment, quick start-up	• Short bunker times for liquids (high rates) • Could be done in parallel with cargo operations (if risk is acceptable): short turnaround times • Vessels do not have to sail to dedicated bunker location: short turnaround times • Flexibility in locations and volumes	• Short bunker times (high rates) • Flexibility in volumes • Scalable with limited additional investment	• Simplified distribution via e.g. container terminals • No infrastructure required: low investment, quick start-up • Short "bunker" times • Vessels do not have to sail to dedicated bunker location: short turnaround times • Modularity & flexibility towards future adaptations or adoption of (other) alternative fuels
Con's	• Low bunker rates/ long bunker time • Low capacity • Relatively high transportation cost per m^3 • Presence of truck on quay might restrict SIMOPS	• High investment and operating costs • Additional threats due to ship motions and ship collisions	• Vessels have to sail to a dedicated bunker location before/after cargo operations: longer turnaround times • High investment costs (in case of fixed installation) • Occupation of port space (in case of fixed installation)	• Low capacity (requires more frequent bunkering) • Occupation of cargo space onboard the ship • Requires multi-modal infrastructure • Relatively high transportation cost per m^3
Typical application	• Low frequency bunkering locations • Early stage bunkering • Different assigned bunkering areas (e.g. public quays or at terminals) • Remote locations	• Seaports with mix of inland and seagoing ships. • Smaller barges for high demand areas (if found to be profitable)	• High frequency bunkering locations with stable and high demand	• Early stage bunkering • Container vessels and cargo vessels • Could be combined with bunker station in future • Bunker location: container terminals

5 HYDROGEN BUNKERING

This chapter provides a more detailed characterization of the specific hydrogen bunkering scenarios taking into account the physical state in which hydrogen can be stored on board. Bunkering scenarios are identified for the following possible storage methods as identified the sub-activity 1.1a report: hydrogen containment systems /1/:

- Pressurized hydrogen;
- Liquid hydrogen;
- Hydrogen carriers:
  - Sodium borohydride;
  - Liquid carriers (e.g. ammonia, LOHC, methanol)[5].

The applicability of the generic bunkering configurations (described in the previous chapter) for the above storage options is also discussed.

5.1 Pressurized hydrogen

There are basically three main methods to bring pressurized hydrogen on board:

1. Hoisting of swappable (mobile) tube- or cylinder-containers;
2. Swapping cylinder racks with forklift;
3. Transfer of gas via hose to fixed tanks on board.

These methods are outlined in the paragraphs below.

5.1.1 Hoisting of swappable tube- or cylinder-containers

The concept of swappable containers is already described in detail in paragraph 4.4.

Figure 3: MS Maas Container ship

Swappable tube-containers or containers with vertical cylinders overcome the problems of long bunkering times and required infrastructure associated with the transfer of gaseous hydrogen. These containers can be filled at a gas production plant and delivered via trailer, train or container vessel to the container terminals where they will be stored in the stack. Alternatively, they can arrive on demand by e.g. trailer and directly loaded from the trailer onto the vessel at the loading dock. When placed in the stack, there will be designated areas for containers with dangerous goods. From the stack they will be taken to the loading dock. Crane drivers will hoist the 'empty' container(s) from the vessel and replace those with the full container(s). Total 'bunkering time' would normally be between 1 – 1.5 hours[6] and will also depend on whether the vessel already needs to be at the container terminal for cargo handling (then the loading can be more efficient). This method of bunkering is foreseen to be used in Future Proof Shipping project MS Maas (see Figure 3).

[5] Formic acid is not identified the sub-activity 1.1a report: hydrogen containment systems /1/ because it is at a very immature stage and also currently not available for shipping (large-scale production is still in research and test phase). However this is a liquid hydrogen carrier and the bunkering scenarios would be the same as for the other liquid carriers.

[6] Including time needed for removal of empty containers and to get the containers from the stack or directly from trailers (arrival on demand).

5.1.2 Swapping cylinder racks with forklift

This bunkering concept is especially suitable for (short-distance) roll-on/roll-off (ro-ro) ferries. The racks can be exchanged with a small forklift, which eliminates the need to refill the cylinders on board during passenger (dis)embarking etc. This process is quite fast and can be completed within half an hour (including decoupling and removal of empty cylinders). The racks with full (and empty) cylinders can be stored at the ferry terminal close to the where the ferry is moored. Because the volume capacity is low (one rack typically consists of 12 cylinders with each a volume of 47 L), frequent swapping might be required. This should normally not be a problem for ferries with short distance routes.

5.1.3 Bunkering to fixed tanks on board via flexible hose(s)

Hydrogen can be transferred with a hose connection from:

- Tubetrailers (TTS);
- Storage at e.g. an onshore installation such as a bunker station or;
- A hydrogen refuelling station for busses/cars with additional disperser for bunkering vessels.

STS bunkering of pressurized hydrogen or bunkering from a floating pontoon with storage on the pontoon is not considered to be a likely scenario. This is due to the required large storage volumes on board of a bunker vessel (because of the low energy density), heavy weight of the containment systems and relatively long bunkering times.

There are two methods of transferring gaseous hydrogen to inland vessels:

1. Pressure balancing
2. With use of a compressor (possibly in combination with precooling)

With both methods it is possible that multiple transfer hoses are used simultaneously.

Pressure balancing is the process of transferring gas with means of creating a pressure differential between the supply storage and the fuel tank on board. This would require a storage pressure higher than the required pressure in the fuel tank. For example, a vessel that requires 350 bar, would need to be supplied by a 500 bar tank. When the hose transfer system is connected, a valve is opened to allow the flow of hydrogen into the fuel tank. The advantage is that compressors are not needed, therefore reducing the capital investment. The main downside of this method is that considerable storage capacity is needed because once the pressure is equalized the transfer of gas stops. For example, transferring 500 kg of hydrogen at 350 bar requires approximately 2000 kg of 500 bar storage, leaving 1500 kg of gas that cannot be utilized. This will result in higher operational costs. There is an option to make use of cascade filling, which is the process of employing numerous smaller containment systems (e.g. cylinders or smaller tubes) in succession. Typically, several large cylinders are used to bring a small cylinder up to the desired pressure, by always using the supply cylinder with the lowest usable pressure first. Then the cylinder with the next lowest pressure is used and this continues till the desired pressure is reached. This will reduce the total amount of storage needed to bunker the vessel at the required pressure. A typical flow rate that is achieved with pressure balancing (and using cascade filling) is approximately 130 kg/h (from 500 bar to 350 bar). Despite the fact that would result in long bunkering times, this rate is in literature referred to as ‘fast fill’ /4/.

The second method is the use of a compressor (e.g. ionic compressor) allowing careful control of the flow rate. The hydrogen supply pressure (at compressor suction line) would then be typically at a low pressure of around 20 bar /4/. This is the most expensive option and also results in very low bunker rates between 30 kg/h ('Slow fill') /4/ and 215 kg/h (or 60 g/s)[7] /3/. This results in long bunker durations easily going up to 4-8 hours depending on bunker volumes. Another report /2/ states that bunkering of large quantities above 1000 kg can even take longer than 12 hours (<85 kg/h), which is based on interviews with many parties developing pilot projects and further confirmed by another Dutch publication /8/. The main reason why the current reported flow rates in literature are so low is due to safety considerations. This is explained in more detail below.

Most study reports claim that when transferring hydrogen on board vessels, the flow rate needs to be carefully controlled to prevent excessive adiabatic heating /3/, /4/. When hydrogen is compressed into storage cylinders, heat is released during adiabatic compression. When left unchecked this could result in softening of the pressure vessels or accelerated degradation leading to catastrophic failure. It is therefore critical that the flow rate of hydrogen is controlled during bunkering.

However, Hexagon Lincoln, a compressed hydrogen tank manufacturer, and HYON, an engineering company for hydrogen integration, indicated feasible bunkering rates of 3000 kg/h based on pressure balancing with cascade filling (from 380 bar to 250 bar). They suspect that the figures mentioned in literature /2/, /3/, /4/ could be related to automobile/truck dispensing and that it is a misconception that maritime bunkering will be similar[8]. Vehicle dispensing at Hydrogen Refuelling Stations include compression, cooling and very high pressures that naturally limit the maximum flow possible. Hexagon & HYON don't make use of a compressor or cooling and use low pressures. Based on flow calculations and tank design HYON confirms that the tanks have no issue with receiving this high flow rate.

This clearly requires more research as it is not exactly clear how the problem of excessive adiabatic heating is overcome. It is recommended to the investigate the maximum feasible (safe) bunker rate that can be achieved with bunkering gaseous hydrogen to inland vessels, taking into account the different methods (cascade filling / compressor) and the problem of excessive heating caused by adiabatic compression.

5.2 Liquid hydrogen

Bunkering of liquid hydrogen is similar to bunkering of LNG. In principle, existing technology for LNG can be modified and adapted to liquid hydrogen. However, this will require considerable engineering and testing before solutions become commercially available.

Bunkering of liquid hydrogen is possible with means of TTS, STS, bunker stations and swappable tank-containers. The latter is less likely to take place because of the risk related to hoisting of liquefied gas containers. If the container falls, liquid might leak from the pressure safety valve and there is a risk of a container falling into the water (safe and timely recovery would prove difficult). The use of swappable containers for bunkering LNG also did not become widely used because of the same issues. For these reasons, liquefied hydrogen is expected to be bunkered using a cryogenic pump and a hose or arm transfer system. For bunkering inland vessels, a flexible hose would be preferred because of operational flexibility.

There are three methods to transfer the liquid hydrogen to the fuel tank:

1. With means of a cryogenic pump;
2. Creating a pressure differential by increasing the pressure in the supply tank with a pressure build-up vaporizer;
3. A combination of the above.

[7] It is unclear if this includes pre-cooling of the gas, which could allow for faster filling rates

[8] However, these studies are clearly written for bunkering of (inland) vessels and not vehicles so it remains unclear what the exact basis is.

The first method is typically used in STS bunkering and bunker stations with larger storage volumes[9]. The second method is sometimes considered for TTS, but would involve longer bunkering times and high risk due to the high pre-pressure needed inside the tank of e.g. 10 barg. For these reasons, a combination of a cryogenic pump and pressure build-up (method 3), would be the most likely method for TTS bunkering. The pressure inside the tank is increased (to e.g. 2.5 barg) to match the required pressure for the pump seals. In some cases there are special seals that only require 1 barg and this could already match the pressure in the tank when the trailer arrives at the bunker location and therefore the increase in pressure would not be needed.

The bunkering station consists of two hose connections, one for the liquid hydrogen and one for the vapour return to the supply tank or boil-off gas system. Inert gas is used prior to the transfer to remove moisture and air in the hoses. Liquid Helium is typically used as inert gas as this will also precool the lines because the boiling point is lower than that of liquid hydrogen /9/.

Bunker parameters such as bunker rates etc. differ depending on the bunkering configuration. More details for hydrogen bunkering via TTS, STS and bunker stations are provided in the paragraphs below.

5.2.1 TTS

An example of a truck-to-ship liquid hydrogen bunkering operation is schematically displayed in Figure 4. This setup makes use of a bunker boom installation on the quay. The trailer is connected with means of a short flexible hose to the filling point. The cryogenic pump is submerged in the storage tank on the trailer. The hydrogen is pumped via the filling point and fixed pipelines to the bunker boom. The outboard side of the bunker boom is a flexible hose, which is connected typically with means of a dry break coupling to the bunker manifold on the receiving vessel.

The trailer could also be connected directly to the receiving vessel with means of a longer flexible hose. However, liquid hydrogen hoses are generally very short to reduce heat influx and would probably not reach from the trailer to the bunker manifold on the vessel. Alternatively, extended loading arms could be used, which are better insulated.

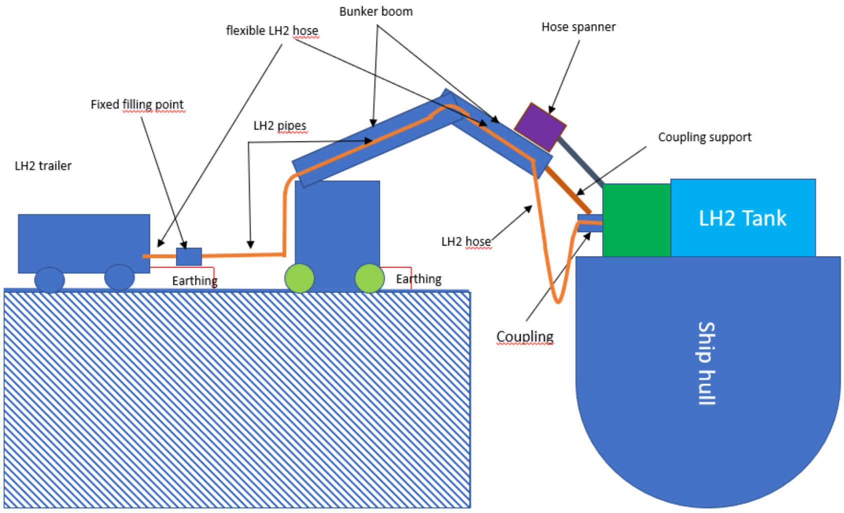

Figure 4: Example of liquid hydrogen truck-to-ship bunkering operation

TTS bunker rates vary between 1000 – 4000 kg/h and the bunker pressure is typically between 5-10 barg depending on the pressure in the fuel tank and pump characteristics. Bunker times are typically between 1-1.5 hours, including time

[9] The large storage tanks have a liquid level creating sufficient hydrostatic pressure at the suction line of the pump. For this reason, the pressure in the tank does not have to be increased by adding vapour to the vapour space.

needed for cooldown, purge and warm-up prior to disconnect. For example, based on bunkering 1000 kg hydrogen, 40 minutes is needed for cooldown, 30 minutes for the transfer (bunker rate of 2000 kg/h) and 30 minutes for purge and warm-up prior to disconnect.

It is also an option to first offload the liquid hydrogen into a local storage tank before bunkering. This would not require refuelling directly from the trailer. This could be a suitable option for inland vessels that don't have a high consumption and return to the same location every day (e.g. ferries). For instance, if a ferry requires 400 kg of liquid hydrogen per day, then a 3000 kg delivery per week per trailer would be sufficient to meet the demand. The downside of this option is the result in losses up to 10% of the 3000 kg due to venting as the double transfer adds more heat and causes the generation of boil-off gas /10/.

5.2.2 STS

Ship-to-ship bunkering of liquid hydrogen can also be considered when the demand is higher. Although there are currently no plans to build inland bunker barges, Moss Maritime has developed a design for a seagoing bunker vessel in cooperation with Equinor, Wilhelmsen, Viking Cruises and DNV. The vessel has a capacity of 500 tonnes (two 4500 m^3 tanks) and can bunker with a maximum rate of 300 m^3/h. The vessel will be loaded at a liquefaction terminal and bunkering will take place at the side of the receiving vessel either moored at the quay, jetty, or buoys.

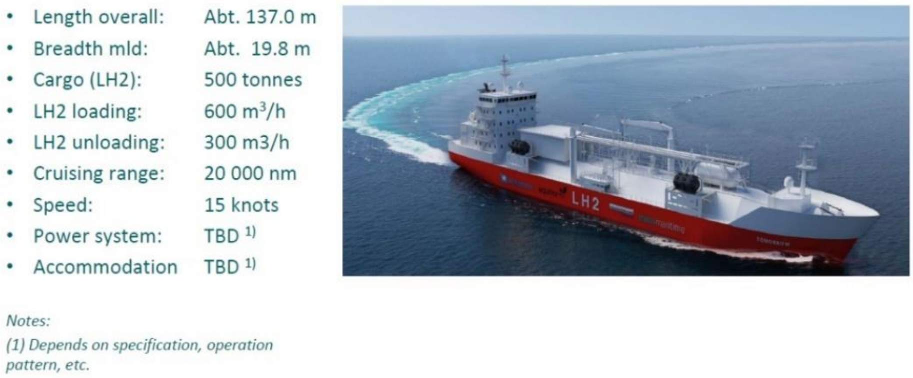

Figure 5: LH2 Bunker vessel Moss Maritime

The cargo capacity for inland bunker barges would normally be smaller than for seagoing bunker vessels, but could still be in the order of 3000 m^3. Bunker rates can range from 30 m^3/hr to 200 m^3/hr depending on the size of the vessel and fuel tanks on board. The bunkering process (inerting, cooling down, transfer, purge, warm-up) is the same as described for truck-to-ship bunkering in paragraph 5.2.1.

5.2.3 Bunker station

While liquid hydrogen refuelling stations for vehicles exist today, a bunker station for refuelling vessels is yet to be developed. Specific information about the design and operation of such a bunker station is not found, although the station design is expected to be similar to LNG bunker stations, which includes one or two tanks (typically bullets), submerged pumps, vacuum insulated pipes and valves and flexible hoses or loading arms. Bunker rates would be in the same order of magnitude as for ship-to-ship bunkering, although a bunker station can normally accommodate a wider range of rates when multiple pumps are installed.

Figure 6: Artist's impression of a bunker station with liquid hydrogen

5.3 Hydrogen carriers

Very little information was found about bunkering of hydrogen carriers, because of their limited use in (inland) shipping. However, bulk transfer of the liquid carriers such as ammonia & methanol (e.g. filling onshore storage tanks with trucks) has been taking place for many decennia and would in principle not differ too much from bunkering a fuel tank on a vessel.

5.3.1 Sodium borohydride

Information about bunkering of sodium borohydride is provided by H2Fuel-Systems, but the details are still under development. $NaBH_4$ can be bunkered as a solid or liquid. As a solid in its crystal form, the plastic storage container can be hoisted on board or the crystals can be transferred mechanically via a conveyor belt similar to grain loading. $NaBH_4$ can also be dissolved in water (with stabilizer) to allow for pump transfer most likely at first from a fixed storage tank onshore and in the future possibly from a truck. The liquid can also be stored in swappable plastic containers that can be hoisted on board. The total bunker duration is estimated between 1-1.5 hours for both hoisting of swappable containers and liquid transfer via hose. The bunker rates for the liquid would be comparable to that for conventional diesel fuel (15-50 m^3/hr). The preferred method of bunkering is not decided yet.

5.3.2 Liquid carriers

Hydrogen carriers such as LOHC, ammonia, methanol are all liquids[10] and bunkering would take place with means of a pump and a hose. All four bunkering configurations are possible and it would start with TTS, followed by the development of bunker vessels and bunker stations when the market becomes more mature. Swapping fuel tanks is also possible when there is no infrastructure. For LOHC this is already considered by H2-industries, containerized LOHC (4x20 ft containers) is hoisted on board.

Swappable containers could also be considered for ammonia as this would considerably reduce the risk of bunkering compared to a pump and hose transfer. However, the risk onboard would increase due to frequent hose connections that have to be made with the fuel system. In addition, industry would prefer bunkering with hose transfer because of

[10] Formic acid is also a liquid hydrogen carrier and the bunkering scenarios would be the same as for the other liquid carriers

experience with ammonia bulk transfers. Swappable containers for methanol are not foreseen because of no obvious benefits in terms of infrastructure & safety compared to a hose transfer.

Previous safety studies carried out by DNV showed very high risk profiles and large safety distances for bunkering ammonia with a hose (due to its high toxicity). This could be showstopper for bunkering ammonia in inland ports and waterways where residential areas and neighbouring industries etc. could be nearby. Hence, bunkering of ammonia in inland ports/waterways via hose transfer is not considered to be a likely scenario. Bunkering of ammonia (to e.g. seagoing vessels) at remote locations in large seaports where there is sufficient space could be possible.

LOHC like Dibenzyltoluene & n-ethylcarbazole is stored and transported similar to diesel. There the bunker methods are expected to be similar to conventional bunkering of diesel. With LOHC there is return cycle as dehydrogenated oil should be removed from the vessel (e.g. via pump / crane / vacuum trailer). This will increase the bunkering time compared to bunkering conventional diesel.

The bunker rates for LOHC would initially be estimated to be the same as for diesel (15-50 m^3/hr), but this would require longer bunkering times (or more frequent bunkering) because the energy density is approximately 5 times lower. To compensate for this difference it expected that the bunker rates will be actually be a factor 4-5 higher, provided that the fuel system including storage tanks on board is dimensioned accordingly (this would not be the case with retrofitting). For ammonia & methanol the difference would be about a factor 2-3.

5.4 Overview of possible IWT bunkering scenarios

This paragraph provides an overview of the identified bunkering scenarios. The following scenarios are identified:

Pressurized hydrogen

1. Swapping containerized hydrogen at container terminal or bunker station with crane. Storage systems could be tube-containers or 20ft/40ft cylinder-containers;
2. Swapping cylinder racks with forklift (for ro-ro ferries);
3. Bunkering via hose (gas transfer) to fixed tanks (e.g. cylinders or tubes) on board from:
    a. Tube trailers (TTS);
    b. Hydrogen refueling stations for busses/cars with additional dispenser for bunkering vessels;
    c. Dedicated bunker station.

   Methods for gas transfer include pressure balancing (possibly in combination with cascade filling) or use of a compressor (possibly in combination with precooling)

STS bunkering of pressurized hydrogen via bunker vessel with hose/crane (or bunkering from a floating pontoon with storage on the pontoon) is not considered to be a likely scenario, considering the weight and number of the containment systems that need to be on board of the bunker vessel / pontoon.

Liquid hydrogen

1. Hoisting of swappable tanks (not considered to be a likely scenario due to safety reasons);
2. Bunkering using hose/arm liquid transfer from:
    a. Trailer (TTS) – with (fixed) onshore bunker boom installation or connected directly via hose (note: if possible because hoses are generally very short to limit heat intake);
    b. Bunker vessel (STS) with hose/arm transfer system. Hose transfer system could include bunker boom;

c. Bunker station (onshore facility or pontoon). Onshore bunker stations could have a pontoon with hose manifold or quay/jetty depending on the location (along river/port area etc.).

Hydrogen carriers

1. Sodium Borohydride:
    a. Solid (crystals): swapping containers or transport of crystals via conveyor belt (similar to grain transport);
    b. Dissolved in liquid (with stabilizer): bunkering via pump & hose from onshore tank or swapping containers with crane;
2. LOHC (stored and transported just like diesel):
    a. Swapping of containers (start-up, does not require infrastructure);
    b. TTS (start-up) – bunkering via pump & hose;
    c. STS (future scenario when demand is high, bunker vessels will operate in port areas);
    d. Bunker stations (future scenario when market is more mature);
3. Ammonia: scenarios same as for LOHC. Swappable containers could reduce risk of bunkering with hose transfer, but risk onboard (leakages) would increase due to frequent hose connections that have to be made with the fuel system. In addition, industry would prefer bunkering with hose transfer because of experience with ammonia bulk transfers;
4. Methanol: scenarios same as for LOHC. Swappable containers are not considered likely because of no real benefits compared to hose transfer.

The feasibility of the above bunkering scenarios for IWT is further discussed in a workshop with the R2HINE participants and stakeholders.

6 WORKSHOP

A workshop was held with the RH2INE consortium participants and stakeholders on the 30th of October 2020 to discuss the first outcomes of sub-activity reports 1.1a and 1.1b. The goal was to identify the most feasible hydrogen bunkering scenarios for IWT. This chapter presents the participants, the structure and the outcomes of the workshop.

6.1 Participants

The following organisations were invited to the workshop:

- Port of Rotterdam
- Duisburger Hafen AG
- RheinCargo GmbH & Co. KGLEC
- Darel
- Provence of Zuid-Holland
- Air Liquide
- Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen
- Rhenus
- Koedood
- Future Proof Shipping
- Covestro
- Imperial Logistics
- HTS Group
- EnergieAgentur NRW
- Reederei Jaegers GmbH

6.2 Structure

The structure of the workshop included two main blocks; (1) the presentation of intermediate results by DNV and (2) a discussion with the participants.

Presentation of intermediate results: The intermediate results of sub-activity 1.1a (containment systems) and 1.1b (bunkering scenarios) were presented by DNV.

Discussion with the participants: A division of the participants was made into three sub-groups to discuss and rank the possible hydrogen bunkering scenarios. Each participant was given the opportunity to provide their point of view on the hydrogen containment systems and bunkering scenarios and the effect on the normal operations and assets. Attention was given to different vessel types that sail on the Rhine; i.e.: Cargo vessel, Pushed Convoy, Cabin vessel, Rhine ferry etc. The outcomes of the discussion were summarized and presented to the other sub-groups followed by a discussion. Relevant issues and points raised during these discussions are included in chapter 7.

6.3 Outcomes: most feasible scenarios

The most feasible hydrogen bunkering scenarios for inland shipping were identified in the short-term (1-5 years), mid-term (5-10 years) and long-term (10-20 years). The scenarios are given below with the main reasons why they were selected.

Short-term (1-5 years): swapping tube-containers with pressurized hydrogen at container terminals

The most feasible scenario for the short-term is swapping pressurized hydrogen in swappable containerized containment systems (tube-containers) at container terminals. There are clear advantages compared to bunkering to fixed tanks on board due to the following reasons:

- Shorter bunkering times. With fixed tanks the bunkering times are currently longer due to limitations in bunker rates (especially relevant for cargo/container vessels that have a higher consumption/demand)11. The conventional operational process of bunkering is eliminated;
- Swappable tanks are in particular suitable for cargo vessels such as container vessels (easy handling) but can also be feasible for bulk/tanker vessels and push boats (in terms of required space). Hoisting above of these vessels at container terminals is more challenging, but still considered feasible;
- The use of swappable tanks seems to be cheaper in the long run compared to fixed tanks. The supply chain is better (no new infrastructure required) and there is better availability (transport of containers per road/train/vessel). However, it requires preparation of the logistical process and more frequent bunkering might be required resulting in additional stops;
- Swappable systems allow for modularity and flexibility. The market can still select the best option for the storage system in the future when the market is more mature. For example, adapted systems can be optimized to allow for fixed tanks with liquid hydrogen or hydrogen carriers in the future.

Pressurized hydrogen has advantages over liquid hydrogen and hydrogen carriers because the fuel and the technology (containment systems) is commercially available. Therefore, only use of pressurized hydrogen is considered to be feasible in the short-term. The low energy density is not considered as a showstopper although more frequent bunkering would be required compared to conventional bunkering of diesel. Bunkering of gaseous hydrogen via hose to fixed tanks on board is not excluded as feasible scenario and could be a good option for smaller (short distance) inland vessels with a low consumption (e.g. ferries, cabin vessels) and that are moored for a longer period time (e.g. overnight) when bunkering can take place. Swappable cylinder racks, however, would be the fastest bunkering option for ro-ro ferries.

Mid-term scenario (5-10 years): bunkering of liquid hydrogen

At the moment pressurized hydrogen is more cost-efficient for inland vessels compared to liquid hydrogen. The high fuel price of liquid hydrogen is expected to improve significantly when first liquefaction plants are built. Rules & regulations are currently not in place for bunkering liquid hydrogen. Requirements for bunkering in (port) regulations and inland waterway legislation first needs to be developed (therefore the short-term solution is pressurized hydrogen). However, liquid hydrogen has a better energy density than compressed hydrogen. Bunkering of liquid hydrogen is similar to bunkering of LNG. In principle, existing technology for LNG can be modified and adapted to liquid hydrogen after extensive engineering and testing before solutions become commercially available. For these reasons liquid hydrogen is still considered as a feasible mid-term scenario for IWT.

Bunkering of liquid hydrogen to inland vessels will probably start with truck-to-ship (limited infrastructure is required). When the market is more mature, bunker barges and/or bunker stations could be developed. The continuous generation of boil-off gas is not considered as an issue due to the good tank insulation, long holding times and frequent consumption.

Long-term scenarios (10-20 year): bunkering of hydrogen carriers

Bunkering of hydrogen carriers is considered to be a long-term scenario for inland shipping mainly because the technologies are still immature and complex systems are required. Sodium borohydride seems the most promising in terms of energy density and safety, but the required technology is still at an early stage of development.

LOHC and methanol are promising in terms of safety, availability & existing supply logistics. In addition, potential re-use of existing diesel storage and infrastructure is an advantage. 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 both LOHC and methanol require a return cycle and complex systems on board, which may be too challenging for the

[11] However, it must be mentioned that there is still uncertainty with respect to the maximum feasible (safe) transfer rate that can be achieved with bunkering gaseous hydrogen to inland vessels. It seems that also high bunker rates are possible reducing the bunkering time significantly in comparison with values reported in literature (see paragraph 5.1.3 & chapter 7 for more information).

inland shipping sector. Nonetheless, it must be noted that ship-to-ship bunkering of a seagoing vessel with methanol is foreseen to take place in 2021. Furthermore, there are currently many ongoing promising developments in China regarding the use of LOHC in inland shipping, which may accelerate the adoption of the fuel.

Ammonia introduces high safety risks that may be a showstopper for bunkering along inland waterways or in small inland ports. In addition, the cracking technology is immature and not ready for large-scale commercial application in the short or mid-term. Further analysis, both technical and economic, is required to assess the potential of using hydrogen carriers in inland shipping.

7 DISCUSSION

This chapter contains a more in-depth discussion about some issues and relevant points found in literature and raised during the workshop and interviews regarding the identified feasible bunkering scenarios. These may require further attention or additional research.

Short-term scenario (1-5 years): Swapping tube-containers at container terminals

The most feasible scenario in the short-term (1-5 year) is swapping tube-containers at container terminals. The interviewed parties indicated that in the beginning, tube-containers will most likely be delivered to the container terminals by trailer. Currently, the pressure in tube-containers for road transport is 350 bar. In the future, the pressure levels might increase and tube-containers with a variety of pressure levels will become available. This calls for standardization of output pressures. A standard output pressure would improve utilization of swappable containers with different pressures as the onboard fuel system does not have to be adjusted.

The following concerns regarding the use of swappable tanks onboard as fuel storage were identified by the DNV ship classification department and brought in the workshop for further discussion:

- The exact solution is unknown (an additional novel item to a novel technology). Detailed and prescriptive requirements for swappable systems/containers as storage on board vessels are currently lacking in the rules & regulations;
- There is an increased risk for leakages as less welded connections are possible and the main tank pipe connections are frequently disconnected;
- In ships, normally the ship components are approved and surveyed during the lifetime as part of the ship. A different quality assurance survey regime needs to be established;
- The safety systems should normally be part of the vessel. It is unclear what does that mean in term of locating the fire detection and extinguishing;
- For compressed hydrogen the tank shall be connected and disconnected to the vent system (a critical safety system that should not be subject to frequent manipulations);
- The container is an enclosed space that increases the risk for explosions in case of a hydrogen leak scenario.

The conclusion during the workshop was that all of the above concerns were already addressed during the design and can be overcome. Details about the solutions were not discussed.

Another issue with swappable containers was brought up during the interviews; when implementing on a large scale along the Rhine, the increase of traffic in the container terminals will increase significantly as many ships will dock at the terminal for a short period of time to swap their containers. In addition, safe handling of the hydrogen containers during hoisting will have to be assured as not all ships can withstand a container dropped on their deck. Furthermore, a large stock of hydrogen containers is required at the container terminal or close to the harbour, increasing the need for capital and storage space, which is already limited in most inland ports.

Two other relevant issues related to swapping containers from possibly bulk vessels and push barges were pointed out during the interviews. The first issue is whether crane drivers feel comfortable performing hoisting activities above these vessels. The holding space for the container(s) might be tight and there is a risk of damaging other parts of the vessel. That brought up a second issue related to insurance. It is unclear whether insurance companies would provide insurance (under the same conditions) for bulk vessels and push barges being loaded with containers at container terminals as this is not part of their normal operation and because of the increased risk of damage during the hoisting activities.

Finally, one of the main reasons mentioned during the workshop why swappable containers would be preferred over fixed tanks is because of the seemingly long bunkering times associated with fixed tanks. This is related to the severe limiting (and controlling) of the flow rate to prevent excessive adiabatic heating that could result in catastrophic failure of the fuel tanks. Filling rates reported in literature for bunkering of (inland) vessels vary between 30 and 215 kg/h /2/, /3/,

/4/. However, during one of the interviews with Hexagon Lincoln and HYON, it became clear that they designed a system that can achieve a filling rate of 3000 kg/h based on pressure balancing and cascade filling. This means that one tube container with an inventory of approximately 1000 kg can be filled in 20 minutes, resulting in reasonable bunkering times comparable to conventional bunkering. This could make bunkering of pressurized hydrogen via hose(s) more feasible in the mid/long-term. It must be noted that swappable systems still have the advantage in the short-term because no infrastructure is needed.

This finding clearly requires more research as it is not exactly clear how the problem of excessive adiabatic heating is overcome. It is recommended to investigate the maximum feasible (safe) bunker rate that can be achieved with bunkering gaseous hydrogen to inland vessels, taking into account the different methods (cascade filling / compressor) and the problem of excessive heating caused by adiabatic compression. Reference is made to paragraph 5.1.3 for more details.

Mid-term scenario (5-10 year): Bunkering of liquid hydrogen

Many interviewed parties did not foresee liquid hydrogen to become one of the main fuels for inland shipping in the upcoming 20 years. The main reasons are the fuel price, limited added value in terms of total CO_2 emission reduction (due to high energy demands for production), challenges regarding storage and continuous generation of boil-off gas and safety requirements. The DNV Energy Transition Outlook 2050 – maritime report /11/ also shows a low uptake of liquid hydrogen in 2050 for the maritime sector primarily due to fuel costs and Capex. Liquid hydrogen is primarily foreseen in niche markets such as cruise vessels and ferries. The report also concludes that compressed hydrogen is more cost-efficient for short-sea and inland vessels compared to liquid hydrogen. However, during the workshop it was expected that the high fuel price of liquid hydrogen is expected to improve significantly when the first liquefaction plants are built, but this is a traditional chicken or the egg dilemma as liquefaction plants will probably not be built if there is no or limited demand (and there is no or limited demand when the fuel price stays high).

Long-term scenario (10-20 years): bunkering of hydrogen carriers

On the longer term hydrogen carriers might become more interesting as technologies mature. sodium borohydride could especially be promising due to the safe storage and bunkering and high hydrogen storage densities. The interviewees were also positive about LOHC, mainly due to the fact that the properties are similar to conventional diesel fuel therefore making it suitable for storage and transport. However, the main downside is that sodium borohydride and LOHC both require a return cycle, which requires more infrastructure and is less cost efficient.

Formic acid is just like LOHC a cyclic fuel. Formic acid is currently in a very early stage in terms of technology readiness level and availability (production is in research and test phase), but would be suitable for storage, transport and bunkering in liquid form similar to conventional fuels. Although currently not available for use in shipping, some reports claim that formic acid shows good potential to be used as hydrogen carrier in inland shipping and short sea in the (far) future /2/, /5/.

Non-cyclic fuels like ammonia and methanol are seen as more ready for the maritime sector than other liquid hydrogen carriers. The DNV Energy Transition Outlook 2050 – maritime report /11/ predicts that ammonia & methanol will dominate the fuel mix for the maritime sector (seagoing vessels) in 2050. Finally, it must be noted that also future large-scale import of hydrogen will influence the price differentiation and choice between the different hydrogen carriers and physical-based storage (pressurized / liquid), which will be an important factor in determining the business case for use in inland shipping. Further analysis, both technical and economic, is required to assess the potential of using hydrogen carriers in inland shipping.

8 CONCLUSION

In this study feasible hydrogen bunkering scenarios are identified for inland navigational vessels. In general, bunkering can take place via four different configurations: truck-to-ship, ship-to-ship, bunker stations and swapping of tank-containers. The applicability of each configuration and the method of bunkering depends on the physical state in which hydrogen (pressurized, liquid, hydrogen carrier) is stored on board inland navigational vessels. The different configurations and scenarios for hydrogen bunkering are described and characterized, which includes a preliminary assessment of advantages and disadvantages.

The results of this study were discussed during a workshop with the RH2INE consortium participants and stakeholders. The most feasible hydrogen bunkering scenarios are identified for the short-term (upcoming 1-5 years), mid-term (5-10 years) and long-term (10-20 years). The scenarios are given below with the main reasons why they are selected.

Short-term (1-5 years): swapping tube-containers with pressurized hydrogen at container terminals

The most feasible scenario for the short-term is swapping tube-containers at container terminals. There are clear advantages compared to bunkering to fixed tanks on board due to the following reasons:

- Shorter bunkering times. With fixed tanks the bunkering times are currently longer due to limitations in bunker rates (especially relevant for cargo/container vessels that have a higher consumption/demand)[12]. The conventional operational process of bunkering is eliminated;
- Swappable tanks are in particular suitable for cargo vessels such as container vessels (easy handling) but can also be feasible for bulk/tanker vessels and push boats (in terms of required space). Hoisting above of these vessels at container terminals is more challenging, but still considered feasible;
- The use of swappable tanks seems to be cheaper in the long run compared to fixed tanks. The supply chain is better (no new infrastructure required) and there is better availability (transport of containers per road/train/vessel). However, it requires preparation of the logistical process and more frequent bunkering might be required resulting in additional stops;
- Swappable systems allow for modularity and flexibility. The market can still select the best option for the storage system in the future when the market is more mature. For example, adapted systems can be optimized to allow for fixed tanks with liquid hydrogen or hydrogen carriers in the future.

Pressurized hydrogen has advantages over liquid hydrogen and hydrogen carriers because the fuel and the technology (containment systems) is commercially available. Therefore, only use of pressurized hydrogen is considered to be feasible in the short-term. The low energy density is not considered as a showstopper although more frequent bunkering would be required compared to conventional bunkering of diesel. Bunkering of gaseous hydrogen via hose to fixed tanks on board is not excluded as feasible scenario and could be a good option for smaller (short distance) inland vessels with a low consumption (e.g. ferries, cabin vessels) and that are moored for a longer period time (e.g. overnight) when bunkering can take place. Swappable cylinder racks, however, would be the fastest bunkering option for ro-ro ferries.

Mid-term scenario (5-10 years): bunkering of liquid hydrogen

At the moment pressurized hydrogen is more cost-efficient for inland vessels compared to liquid hydrogen. The high fuel price of liquid hydrogen is expected to improve significantly when first liquefaction plants are built. Rules & regulations are currently not in place for bunkering liquid hydrogen. Requirements for bunkering in (port) regulations and inland waterway legislation first needs to be developed (therefore the short-term solution is pressurized hydrogen). However, liquid hydrogen has a better energy density than compressed hydrogen. Bunkering of liquid hydrogen is similar to bunkering of LNG. In principle, existing technology for LNG can be modified and adapted to liquid hydrogen after

[12] However, it must be mentioned that there is still uncertainty with respect to the maximum feasible (safe) transfer rate that can be achieved with bunkering gaseous hydrogen to inland vessels. It seems that also high bunker rates are possible reducing the bunkering time significantly in comparison with values reported in literature (see paragraph 5.1.3 & chapter 7 for more information).

extensive engineering and testing before solutions become commercially available. For these reasons liquid hydrogen is still considered as a feasible mid-term scenario for IWT.

Bunkering of liquid hydrogen to inland vessels will probably start with truck-to-ship (limited infrastructure is required). When the market is more mature, bunker barges and/or bunker stations could be developed. The continuous generation of boil-off gas is not considered as an issue due to the good tank insulation, long holding times and frequent consumption.

Long-term scenarios (10-20 year): bunkering of hydrogen carriers

Bunkering of hydrogen carriers is considered to be a long-term scenario for inland shipping mainly because the technologies are still immature and complex systems are required. Sodium borohydride seems the most promising in terms of energy density and safety, but the required technology is still at an early stage of development.

LOHC and methanol are promising in terms of safety, availability & existing supply logistics. In addition, potential re-use of existing diesel storage and infrastructure is an advantage. 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 both LOHC and methanol require a return cycle and complex systems on board, which may be too challenging for the inland shipping sector. Nonetheless, it must be noted that ship-to-ship bunkering of a seagoing vessel with methanol is foreseen to take place in 2021. Furthermore, there are currently many ongoing promising developments in China regarding the use of LOHC in inland shipping, which may accelerate the adoption of the fuel.

Ammonia introduces high safety risks that may be a showstopper for bunkering along inland waterways or in small inland ports. In addition, the cracking technology is immature and not ready for large-scale commercial application in the short or mid-term. Further analysis, both technical and economic, is required to assess the potential of using hydrogen carriers in inland shipping.

A more in-depth discussion about some issues and relevant points found in literature and raised during the workshop and interviews regarding the identified bunkering scenarios is included in chapter 7. These may require further attention or additional research.

As a final note, it is clear that swapping of containers have apparent advantages over the other configurations and bunkering scenarios especially in the short-term. However, this would imply adopting a completely different approach towards bunkering in comparison to how conventional bunkering of diesel takes place today.

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