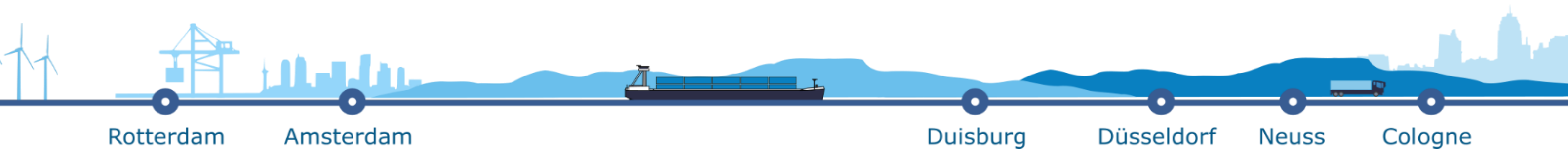

# RH$_2$INE Kickstart Study

## Main Findings & Strategic Roll-Out Plan

RH$_2$INE

Rhine Hydrogen Integration

Network of Excellence

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# List of abbreviations

| | |
|---|---|
| Bevi | Besluit Externe Veiligheid Inrichtingen (Decree on External Safety of Installations) |
| BImSchG | Bundes-Immissionsschutzgesetz |
| BImSchV | Bundes-Immissionsschutzverordnung |
| CBA | Cost-Benefit Analysis |
| CCNR | Central Commission for Navigation on the Rhine |
| CESNI | Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure (European committee for drawing up standards in the field of inland navigation) |
| $CO_2$ | Carbon Dioxides |
| ES-TRIN | European Standard laying down Technical Requirements for Inland Navigation vessels |
| EU | European Union |
| FC | Fuel Cell |
| Ft | Foot |
| IBC | Intermediate Bulk Containers |
| ICE | Internal Combustion Engine |
| IGF | International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels |
| ISO | International Organization for Standardization |
| IWT | Inland Waterway Transport |
| KAS | Kommission für Anlagensicherheit |
| LNG | Liquefied Natural Gas |
| LOHC | Liquid Organic Hydrogen Carriers |
| MEGC | Multiple-Element Gas Container |
| $NaBH_4$ | Sodium Borohydride |
| $NaBO_2$ | Sodium Metaborate |
| NOx | Nitrogen Oxides |
| PGS | Publicatie Gevaarlijke Stoffen (Publication Series on Hazardous Substances) |
| PM | Particulate Matters |
| RVIR | Rhine Vessel Inspection Regulations |
| RPR | Police Regulations for the Navigation of the Rhine |
| QRA | Quantitative Risk Assessment |
| SIMOPS | Simultaneous Operations |
| STS | Ship-to-Ship |
| TTS | Truck-to-Ship |
| UNECE | United Nations Economic Commission for Europe |



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# Introduction

***$RH_2INE$ Programme: Hydrogen as a fuel for inland waterway transport***

$RH_2INE$ (Rhine Hydrogen Integration Network of Excellence) is a programme initiated by the Dutch province Zuid-Holland and the ministry of Economic Affairs of the German state of Nordrhein-Westfalen, in close cooperation with several private and public stakeholders, such as national, regional and port authorities, ship-owning companies and operators, maritime suppliers and hydrogen producers and suppliers. Objective of this programme is to facilitate the implementation of hydrogen as a fuel for inland waterway transport. In a letter of intent, the private and public stakeholders committed to the ambition of having 50-100 operational hydrogen propelled inland vessels in 2030.

As a first step in the $RH_2INE$ programme, the province Zuid-Holland, the ministry of Economic Affairs of Nordrhein-Westfalen (NRW-MWIDE), the Port of Rotterdam, duisport (Duisburg) and RheinCargo (representing the ports of Neuss/Düsseldorf and Cologne) initiated the $RH_2INE$ Kickstart Study to investigate the requirements for the implementation of hydrogen as a propulsion fuel for inland vessels on the corridor between Rotterdam and Cologne. The main focus of the $RH_2INE$ Kickstart Study is the requirements for the ports and regional governments to facilitate the implementation of hydrogen in IWT.

Simultaneously with the $RH_2INE$ Kickstart Study, there are several other activities within the $RH_2INE$ programme, such as the lobby for regulation and funding, and the regional collaboration with private stakeholders (in NRW and in Zuid-Holland). A major achievement is that several ship-owning companies are in the process of developing, planning, financing and building hydrogen fuelled inland vessels. This is done in close cooperation with the suppliers of maritime and hydrogen equipment as well as suppliers of hydrogen. This process and these stakeholders have been a main source of information during the $RH_2INE$ Kickstart Study.

***$RH_2INE$ Kickstart Study***

The $RH_2INE$ Kickstart Study started in March 2020 and was structured according to figure 1. The first activity (framework conditions) is split in two sub-activities, scenario building and regulatory & safety analysis. Design and Location Study are the other two 'technical' activities. This strategic rollout plan is part of the activity on communication and dissemination.

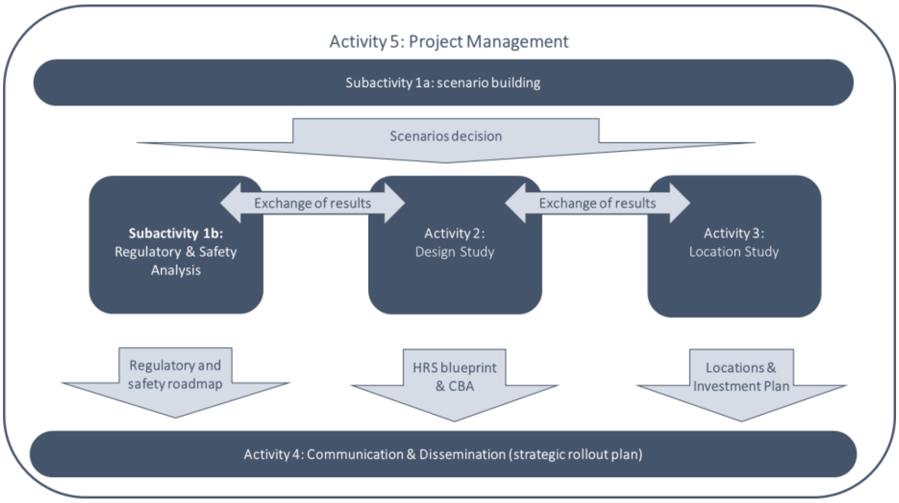


*Figure 1: Project structure of RH2INE Kickstart Study*

The sub-activity of scenario building was focussed on assessing the various (technical) scenarios for the use of hydrogen in (inland) vessels as well as identifying three scenarios with regards to the potential demand of hydrogen by IWT. Within this activity, a study was commissioned by the three ports and executed by DNV.

Based on the outcomes of the most feasible scenarios, the next step was analysing the current regulatory framework, its gaps with regards to the use and bunkering of hydrogen and the safety aspects for bunkering hydrogen (e.g. the safety distances). Within this activity, a study was commissioned by the two regional governments and carried out by DNV.

After these framework conditions were covered, and mainly focussed on the most feasible short-term scenario, the design study was performed. The design study addressed the technical requirements and the blueprint of the bunkering of hydrogen. Furthermore, it included a cost-benefit analysis. This study was done by ZBT and Energy Engineers and commissioned by the five beneficiaries of the $RH_2INE$ Kickstart Study.


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The last technical study was the location study. Based on the most feasible scenarios and bearing in mind the outcomes of the studies on the regulatory and safety aspects and the design, during this activity the main implications for the physical bunkering locations were studied, including the demand scenarios for the ports involved in the $RH_2INE$ Kickstart Study. Besides, a qualitative analysis for mid- and long-term scenarios were included. This study was commissioned by the five beneficiaries and executed by Buck Consultants International, CE Delft and KIWA.

***Readers' guide***

In this document, the main findings and results of each of these above-mentioned studies are discussed in the chapters 1-4, using the studies performed by the external experts. These outcomes are based on the input of the relevant stakeholders and – where necessary – reviewed by them. Detailed descriptions of these studies are given in the reports of the external experts. Chapter 5 is focussed on the conclusions from these studies and the recommendations for the further roll-out of these outcomes.



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# 1. Scenarios

During the scenario building, as the first step in the RH$_2$INE Kickstart study, the most feasible scenarios for the use, storage and bunkering of hydrogen were assessed. The scenario building is especially focussed on the implications of the use of hydrogen for the (port) infrastructure. Within the programme RH$_2$INE the ship-owning companies are involved in the use of hydrogen on-board of inland vessels. These ship-owning companies are all focussed on the use of hydrogen in fuel cells, as a zero-emission solution, rather than the use of it in internal combustion engines (ICE). However, the hydrogen infrastructure could also be used for providing hydrogen to vessels with (dual-fuel) hydrogen ICEs. As especially the activity of scenario building – in gaining market information on technological development – required the involvement of various stakeholders, consulted during interviews and workshops. The results described below can be found in the reports of DNV (2021a, 2021b and 2021c), unless referred otherwise.

## 1.1 Containment and storage

The first step in analysing the scenarios was the assessment of the storage and containment scenarios, the nature of the containment system and storage method could affect the choice in bunkering scenario. In Table 1, an overview of these storage methods is given. This can be roughly divided into physical based (pressurised/compressed and liquid hydrogen) and material based, with the different forms of hydrogen carriers.

*Table 1: Overview of the characteristic of the various $H_2$ storage methods and containment systems (DNV, 2021a)*

| ***Storage method*** | **Containment system** | **Pressure** | **Temperature** | **State of aggregation** |
|---|---|---|---|---|
| | *Physical-based* | | | |
| *Pressurised* | Pressure cylinders/tubes (type I; II; III; IV) placed in cylinder racks, or 20/40 ft ISO tube or cylinder containers | 200-1000 bar | Ambient | Gas |
| *Liquid* | Super insulated tanks (IMO type C). Fixed tanks or ISO tank containers | Atmospheric – 5 bar | -250 to -245 °C | Liquid |
| | *Material-based* | | | |
| *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<br>2. $CO_2$ tanks | 1. Atmospheric<br>2. 12-25 bar | 1. Ambient<br>2. -35 to -15 °C | 1. Liquid<br>2. Liquid |
| *$NaBH_4$* | Crystal: Storage similar to salt (plastic containers)<br>Liquid: Plastic containers, IBC tanks, storage for corrosive liquids | Atmospheric | Ambient | Solid (crystal)<br>Liquid (dis-solved in water) |
| *Ammonia* | 1. Insulated tanks<br>2. Insulated pressure tanks | 1. Atmospheric<br>2. 10-30 bar | 1. -34 °C<br>2. Ambient | 1. Liquid<br>2. Gas |

As diesel has a relatively high energy density, alternative fuels are always compared with diesel. Figure 2 shows the energy density of hydrogen in the different forms including its storage system (compared to LNG and diesel). Although they are not able to reach the energy density of diesel, hydrogen carriers such as $NaBH_4$, methanol and ammonia have a relatively high volumetric energy density (higher than LNG). Taking into account its storage system, pressurised hydrogen – even under higher pressure – has a low energy density.



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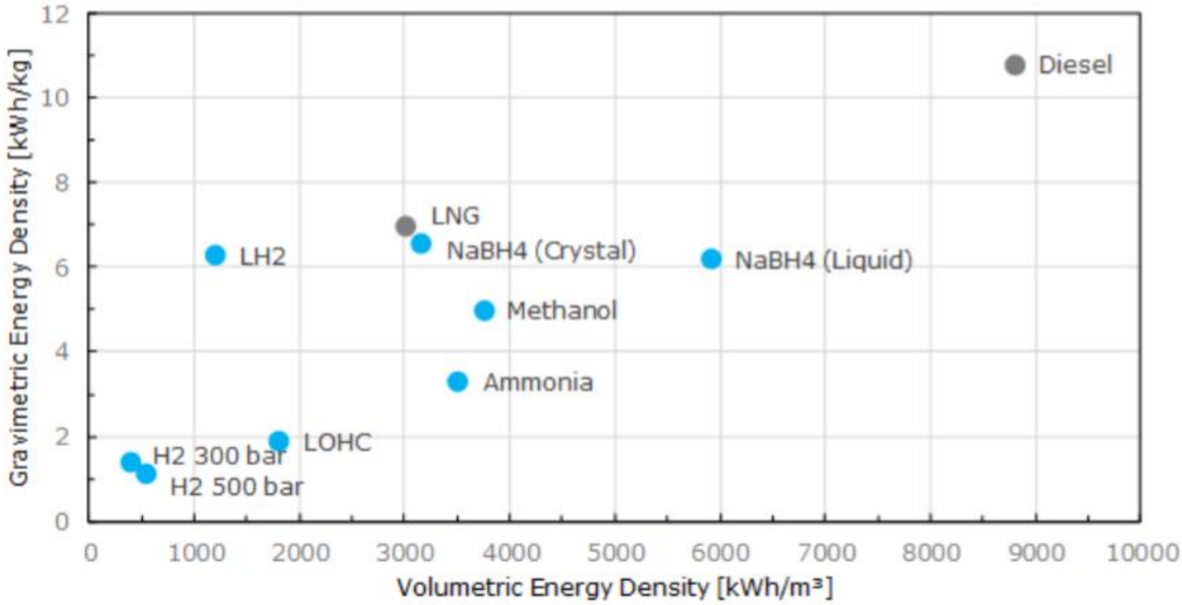


*Figure 2: Energy density hydrogen/hydrogen carriers including storage system compared to diesel and LNG (DNV, 2021a)*

Although energy density is an important element, for a full assessment of the (current) feasibility of these scenarios, other characteristics (technological maturity, safety, fuel availability and bunkering time) are needed to be addressed. In the sections below, a short description of the hydrogen form and the outcomes of this analysis are given.

### 1.1.1 Pressurised hydrogen

Pressurised – or compressed or gaseous – hydrogen is currently seen as the most mature method of storing hydrogen, therefore also the most applied method in the present. However, as mentioned above, a strong disadvantage of this storage method is the low energy density of pressurised hydrogen (including its storage system). Under higher pressure, it is possible to slightly improve its volumetric energy density, saving some (cargo) space. The storage of pressurised hydrogen can be done in type I-IV cylinders or tubes (a short description of them is given under chapter 3). This storage can be done either with a fixed installation on board of a vessel or in (swappable) systems, 20 or 40 ft containers or in cylinder racks. As the filling these cylinders/tubes have high bunkering times, the use of swappable, prefilled tanks – rather than bunkering fixed tanks – makes it easier to integrate this in the operations of an inland vessel.

### 1.1.2 Liquid hydrogen

More favourable regarding the energy density is liquid hydrogen, cooled to -253 °C and stored in super insulated tanks (or eventually, tank containers). As the temperature increases over time – increasing the pressure in the containment system – boil-off is needed to prevent overpressure. The super insulated tanks are used to minimise these boil-off/losses. This is also a main disadvantage of the use of liquid hydrogen.

### 1.1.3 Hydrogen carriers

Besides the physical-based storage of hydrogen, there are also several material-based storage methods. There are several methods, in which hydrogen molecules are bonded to other molecule structures or other materials, in hydride storage or by absorption.

***Liquid organic hydrogen carriers (LOHC)***

LOHC is the principle of binding hydrogen in a liquid organic substance. There are several available options, but only a few are feasible for the use onboard of vessels (HyNed et al., 2020). It can be stored in conventional steel tanks, as also used for storing diesel, which enables the use of existing infrastructure (bunker vessels, trailers or containers). When used onboard of a vessel, LOHC$^+$ (charged with $H_2$) and LOHC$^-$ (discharged) have to be stored separately (using separate, multi-chamber or membrane tanks). Disadvantages are the cleaning after dehydrogenation and the high temperatures needed for (de)hydrogenation.


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***Methanol***

Methanol can also be stored under the same conditions as diesel. Another advantage of methanol is the wide use and availability. Methanol can also be used in ICEs, for the use in fuel cells, there are two options: Either in a direct methanol fuel cell or reformed to produce hydrogen for a hydrogen fuel cell. However, in each of these cases, to avoid carbon emissions, $CO_2$ should be stored onboard in an additional storage system. This can be done in pressurised form (at a pressure of 45-65 bar) or in refrigerated to liquid form (the latter form is mentioned in table 1).

***Sodium Borohydride ($NaBH_4$)***

$NaBH_4$ is a metal hydride for storing hydrogen in a solid substance (powder form, similar to salt). It is also possible to store it in liquid form (as shown in table 1). A dehydrogenation system with pure water is required to release the hydrogen. The spent fuel ($NaBO_2$) have to be stored separately. Although the technology is still immature for direct wide implementation, further research (like currently in the H2SHIPS project) could result in higher technological maturity in the future.

***Ammonia***

Ammonia ($NH_3$) is a widely used industrial product with a well-developed production and highly mature storage technologies. It can be used directly, but for the use in hydrogen fuel cells, a cracker with cleaning and purifying equipment is needed to extract the hydrogen and – to avoid nitrogen emissions – nitrogen should be stored. Main disadvantage is the high toxicity of ammonia, causing major environmental and safety concerns.

### 1.1.4 Overall conclusions on containment and storage

In table 2 an overview of the (dis)advantages of each of these storage methods and the main findings can be seen. There are some promising technologies among the hydrogen carriers, however each of them currently has a lower technological maturity, and some complexities in dehydrogenation and storage of spent fuel/ CO2/nitrogen. Although its low energy density, the maturity of pressurised hydrogen is a deciding factor in its feasibility (at least on the short term).

*Table 2: Overview of (dis)advantages and findings of the various fuel systems (DNV, 2021a)*

| *Fuel system* | Pros | Cons | Findings |
|---|---|---|---|
| *Pressurised H2 Swappable tanks* | Bunkering time<br>Fuel availability<br>Maturity | Energy density (incl. storage)<br>Safety | Most popular and applied for inland vessels<br>Reduced bunkering time<br>Possible safety issues (onboard) |
| *Pressurised H2 Fixed tanks* | Fuel availability<br>Maturity<br>Safety | Energy density (incl. storage)<br>Bunkering time | Most popular and applied for inland vessels<br>Only feasible on small vessels due to long bunkering times (expected to improve in future) |
| *Liquid H2* | Bunkering time<br>Maturity | Energy density (incl. storage)<br>Fuel availability<br>Safety | Low uptake due to fuel costs, CAPEX, many safety requirements and boil-off gas<br>Possibly only niche markets, such as cruise vessels and ferries |
| *LOHC* | Bunkering time<br>Fuel availability<br>Safety | Energy density (incl. storage)<br>Technology/ Maturity | Immature, not ready (yet) for maritime application, perhaps in a few years<br>Safety advantages<br>Storage of spent fuel needed |
| *Methanol* | Energy density (incl. storage)<br>Bunkering time<br>Fuel availability | Technology/ Maturity<br>Safety | Still immature<br>Requires reformer onboard and $CO_2$ storage<br>Some safety concerns (although less than ammonia) |
| *NaBH4* | Energy density (incl. storage)<br>Bunkering time<br>Fuel availability<br>Safety | Technology/ Maturity | Very promising, but technology still immature (current research)<br>Storage of spent fuel needed |
| *Ammonia* | Energy density (incl. storage)<br>Bunkering time<br>Fuel availability | Technology/ Maturity<br>Safety | Still immature<br>Safety concerns<br>For FC, requires cracker (to produce H2)<br>Production (storage) of nitrogen |


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## 1.2 Bunkering

There are four bunkering configurations assessed in the scenario building. There is an interdependency between the bunkering method, the physical state of hydrogen and the (onboard) storage. The bunkering configurations identified by DNV and assessed during its study are:

***Truck-to-ship bunkering (TTS)***

TTS bunkering is the bunkering of a vessel by a truck positioned on a quay, this can be done either directly from truck to fuel tank by flexible hoses or indirectly through a fixed connection on shore. The bunkering can take place in a port or – if possible, on wider waterways with lower currents – along the river, where a vessel is moored safely. This bunkering method is already common practice for the bunkering of LNG, with dedicated locations in the ports of Rotterdam, Antwerp and Amsterdam. As TTS involves usually lower bunkering rates, it is more feasible for vessels with lower tank capacity or requires multiple trucks for higher tank capacity. Due to its flexibility and low investment costs, it is especially suitable for the first phase of implementing an alternative fuel.

***Ship-to-ship bunkering (STS)***

STS bunkering is currently the most dominant configuration for the bunkering of diesel, because of the high bunkering rates and the possibility to bunker during normal operations. This should be assessed for bunkering of hydrogen during (un)loading operations, bunkering of hydrogen during sailing operations doesn't seem feasible on the short-term. If not restricted by port regulations and in presence of hydrogen infrastructure, STS bunkering can also provide a flexible solution. However, the investment in bunker barge, hydrogen supply infrastructure and the operating costs are a main drawback.

***Bunker station-to-ship bunkering (BTS)***

Bunker stations with one or more fixed storage tanks can provide hydrogen with a flexible hose to a vessel moored at a quay, jetty or pontoon. Bunker stations require investment costs, which can be kept limited compared to STS, if scaled based on (increasing) demand. There are some options, a bunker station onshore or a floating facility. The latter provides some flexibility, especially in the case of limited space, but should be assessed on its risks of e.g. collision or capsizing. A bunker station is less flexible, as a vessel has to navigate towards the specific location before or after its cargo operations.

***Container-to-ship bunkering (CTS)***

The last option is CTS bunkering with swappable tank containers, in which prefilled containers can be loaded and the empty H2 containers can be unloaded with the use of a container crane (or alternatively, with an onboard crane). In this case, it will be handled at a regular container terminal as a standard dangerous goods container. This solution provides some modularity and flexibility, as it doesn't require high investments and the swapping of containers can be done in a shorter period of time than regular bunkering. Main drawbacks are the low capacity of these tanks and that the tank containers occupy cargo space.

A short overview of the bunkering configurations, the main (dis)advantages and the potential use are given in table 3.

*Table 3: Bunkering configurations (DNV, 2021b)*

| | Truck-to-ship | Ship-to-ship | Bunker station | Swappable containers |
|---|---|---|---|---|
| ***Typical volumes*** | 50 - 100 Nm$^3$ | 100 – 1000 Nm$^3$ | All volumes | 20 – 40 Nm$^3$ per tank |
| ***Pros*** | Flexible<br>No infrastructure required: low investment, quick start-up | Short bunker times for liquids (high rates)<br>Could be done in parallel with cargo operations (if risk is acceptable): short turnaround times<br>Vessels do not have to sail to dedicated bunker | Short bunker times (high rates)<br>Flexibility in volumes<br>Scalable (with limited additional investments) | Simplified distribution (e.g. container terminals)<br>Use of existing infrastructure at container terminals, quick start-up<br>Short "bunker" times |



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| | | location: short turnaround times<br>Flexibility in locations and volumes | | Vessels do not have to sail to dedicated bunker location: short turnaround times<br>Modularity & flexibility towards future adaptations or adoption of (other) alternative fuels |
| ***Cons*** | Low bunker rates/long bunker time<br>Low capacity<br>Relatively high transportation cost per m$^3$<br>Presence of truck on quay might restrict SIMOPS | High investment and operating costs<br>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<br>High investment costs (fixed installation)<br>Occupation of port space (fixed installation) | Low capacity (requires more frequent bunkering)<br>Occupation of cargo space onboard the ship<br>Requires multi-modal infrastructure<br>Relatively high transportation cost per m$^3$ |
| ***Typical appli-cation*** | Low frequency bunkering locations<br>Early stage bunkering<br>Different assigned bunkering areas (e.g. public quays or at terminals)<br>Remote locations | Seaports with mix of inland and seagoing ships.<br>Smaller barges for high demand areas (if found to be profitable) | High frequency bunkering locations with stable and high demand | Early stage bunkering<br>Container vessels and cargo vessels<br>Could be combined with bunker station in future<br>Bunker location: container terminals |

## 1.3 Outcomes: Selection of scenarios

The result of this study is a selection of most feasible scenarios, which can be used in the further assessment of the RH2INE Kickstart Study. During the scenario building, it became clear that there are different scenarios feasible for the short-term (1-5 years) compared to mid (5-10 years) or long term (>10 years). The technological maturity and fuel availability are deciding factor for the short-term feasibility of the storage systems, while for the bunkering scenarios flexibility and low investment are important elements. Assuming further technological developments, other factors like the energy density are more determining for the longer term. This results in a scenario for the short-term period, which had been assessed in more detail in the further studies, and mid- and long-term scenarios.

***Short-term scenario: Pressurised hydrogen in swappable tanks***
The outcome for the short-term is that the use of pressurised hydrogen is the most feasible storage scenario, as the fuel and the technology are currently commercially available. The most feasible bunkering scenario is the use of swappable tank containers, allowing modularity and flexibility, with shorter bunkering times than with fixed tanks and only minor investments needed on the bunkering location (if there's already equipment available for handling containers). However, the study of ZBT and EE (as part of the design study) showed that there are still optimisations of the filling stations needed.

***Mid-term scenario: Liquid hydrogen***
For the mid-term, there is a potential for liquid hydrogen, mainly because of its higher energy density than pressurised hydrogen. Important conditions are lower prices due to the construction of liquefaction plants and that the requirements are improved by the development of regulation and standards.

***Long-term scenario: Hydrogen carriers***
Although still immature and it requires complex systems (storage of spent fuel, return cycle), the high energy density of some of the hydrogen carriers makes them promising for the long-term scenario. On the short-term, methanol is more likely to be of interest for seagoing vessels rather than for inland vessels. There are some promising developments with LOHC in IWT in China, which may accelerate its adoption. $NaBH_4$ is still at an early stage of development, but promising because of its energy density and safety.


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## 1.4 Demand

DNV (2021c) also made a qualitative assessment of the industry's perspective of hydrogen compared to other alternative fuels as well as a quantitative assessment of the demand for hydrogen in IWT on the Rhine between 2020 and 2040.

### 1.4.1 Scenarios and qualitative assessment

In the qualitative assessment, the current perspective of industry on hydrogen compared to other alternative fuels is assessed based on interviews and workshops with relevant stakeholders. Using this comparison as a starting point, the next step was performing the same assessment for 2030 under three different scenarios.

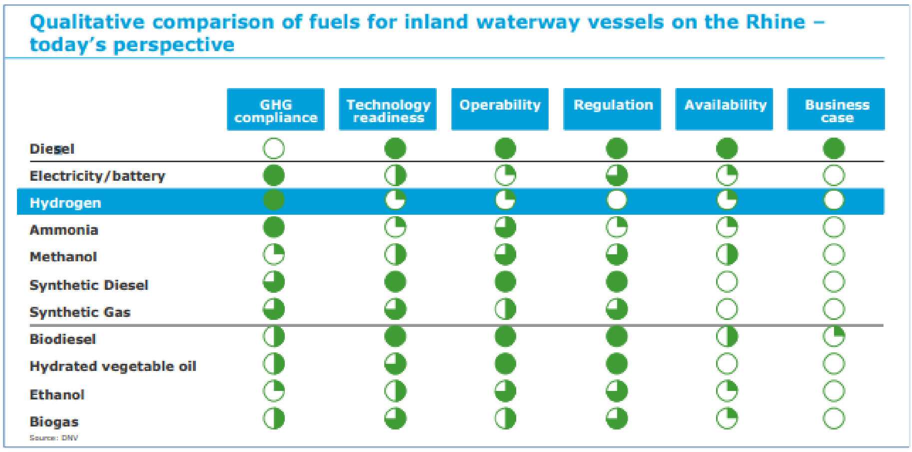


*Figure 3: Qualitative comparison of fuels for inland vessels on the Rhine - today's perspective (DNV, 2021c)*

The three scenarios used for this assessment are:

***Scenario 1: Current instruments, moderate technology development pace***

This scenario is based on the current political instruments and without any specific political ambitions considering limiting GHG emissions or carbon pricing. However, it considers (existing) EU and national funds and favourable financing conditions supporting CAPEX of first fuel cell and hydrogen projects (covering no more than two thirds of the price gap). This scenario considers moderate technology development pace with liquid hydrogen replacing pressurised hydrogen between 2025 and 2030, and viable use of material based hydrogen by 2030. Concerning the market development, it assumes that the number of inland vessels remain stable with about 80 newly built vessels per year, of which 10% is equipped with alternative technologies. For the existing vessels, only 2% of the vessels in need of retrofitting (assumed on 20 years) are retrofitted with alternative fuels. It is assumed that one third of these vessels equipped or retrofitted with alternative fuels will be running on hydrogen.

***Scenario 2: Green Deal, medium technology development pace***

This scenario is based on the ambitions of the Dutch (maritime) Green Deal. [1] It assumes that this ambition is backed with political instruments, such as (higher) $CO_2$ pricing and EU and national funds providing CAPEX support, resulting in a break even business case for hydrogen on newly built vessels. It considers a medium pace with regards to the technological development, viable liquid hydrogen by 2025 and hydrogen carriers by 2030. It assumes the same numbers of newly built vessels and retrofit as under scenario 1, however with an increasing number of ship-owners deciding to apply zero emission technologies, of which one third will be running on hydrogen.

[1] Green Deal Zeevaart, Binnenvaart en Havens: https://www.greendeals.nl/green-deals/green-deal-zeevaart-binnenvaart-en-havens


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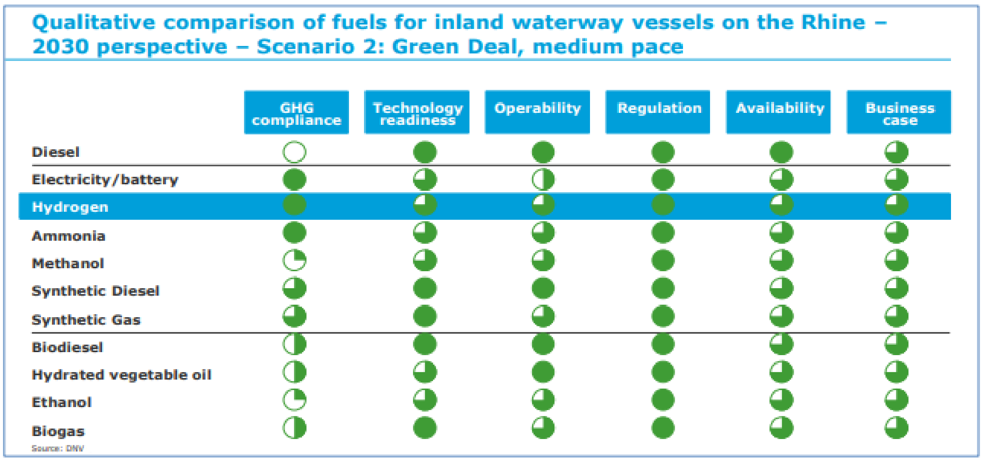


*Figure 4: Qualitative comparison of fuels for inland vessels on the Rhine - 2030 perspective - scenario 2 (DNV, 2021c)*

***Scenario 3: Zero GHG emissions by 2050, rapid technology development***

This scenario assumes that IWT is GHG emission free by 2050 and 80% emission reduction by 2040. This is backed by (increased) $CO_2$ pricing, EU and national funds and favourable financing conditions, resulting in a positive business case for hydrogen compared to conventional fuels and partially for retrofits. It assumes a rapid technological development with viable material based hydrogen between 2025 and 2030. While the same numbers of newly built vessels and retrofit as under the other scenarios, it assumes an increasing share of them being equipped or retrofitted to zero emission technologies, of which one third on hydrogen.

## 1.4.2 Quantitative assessment

The quantitative assessment was focussed on the potential development of demand on hydrogen under the three above-mentioned scenarios. According to DNV (2021c), the total fuel consumption of inland vessels operating on the Rhine is around 2.6 million tons diesel per year, which is in energy demand the equivalent of an annual consumption of 920 000 tons hydrogen. The expected demand under the three scenarios are given in table 4. This equals a share of 1% (under scenario 1) to 11% (under scenario 3) for hydrogen consumption as part of the total energy demand by the inland vessels operating on the Rhine. This reduces annually 90 000 to 950 000 tons $CO_2$.

*Table 4: Expected hydrogen consumption (in tons/year) under the three scenarios (DNV, 2021c)*

| *Hydrogen (t/year)* | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| *2030* | 5 000 | 18 000 | 48 000 |
| *2040* | 10 000 | 36 000 | 104 000 |

The development of this hydrogen consumption – with the intermediate years included – can be seen in figure 5.

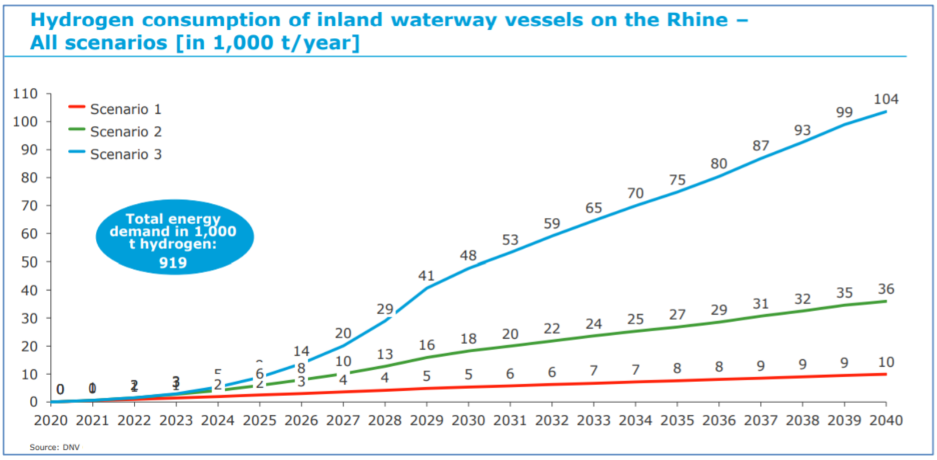


*Figure 5: Hydrogen consumption of inland vessels on the Rhine in the three scenarios (in 1 000 t/year) (DNV, 2021c)*

# 2. Regulatory and safety analysis

The second step was the assessment of the safety and regulatory aspects. Based on the outcomes of the scenario building study, in this assessment the use, bunkering and storage of pressurised hydrogen (under 300-500 bar) stored in swappable containers had been considered. The results described below can be found in the reports of DNV (2021d and 2021e), unless referred otherwise. This analysis includes three elements, the water-based regulation and standards (onboard of vessels and the hydrogen bunkering to vessels), the land-based regulations and standards for systems supplying hydrogen in the Netherlands and Germany and the safety distances for hydrogen installations and bunkering.

## 2.1 Water-based regulation and standards

The analysis on the water-based regulation and standards regulatory aspects for the onboard use and bunkering of hydrogen (maritime (IGF code) and IWT (ES-TRIN; CCNR) regulations are included) had been taken into account partially in the scenario building, as it is a factor in the feasibility of the bunkering and containment scenarios. In table 4, an overview of the identified gaps in water-based regulation and standards is given. The report of DNV (2021d) gives an overview of recommendations to solve these gaps.

A detailed overview of relevant organisations and regulations is given in the report of DNV (2021d), but it is important to notice that there are several relevant authorities involved for the transport of dangerous goods (UNECE for ADN; also included in EC directive for the inland transport of dangerous goods), for the technical requirements of inland vessels (CCNR for the Rhine Vessel Inspection Regulations; EC for its directive on technical requirements; cooperating within CESNI on an integration of these regulations in ES-TRIN) and the handling and control of hazards involving dangerous goods (EC for Seveso III, national authorities).

*Table 5: Overview of identified gaps with the gap categories Legal (L), Harmonisation (H) and Knowledge (K) (DNV, 2021d)*

| ***Gap no.*** | **Gap description** | **Gap category** |
|---|---|---|
| | *IGF code: International code of safety for ships using gases or other low flashpoint fuels* | |
| *1a* | Use of fuel cells is not regulated by IMO. Technical provisions for fuel cells are missing in the IGF Code. | L, K |
| *1b* | Detailed and prescriptive requirements for storage (including swappable systems/containers) and use of hydrogen as fuel in ships are missing. Provisions for bunkering gaseous & liquid hydrogen (bunker station shipside etc.) are also missing. | L, K |
| | *ES-TRIN: European Standard laying down Technical Requirements for Inland Navigation vessels* | |
| *2a* | The ES-TRIN provides general provisions for low flashpoint fuels (Ch. 30; Appendix 8) but specific construction requirements regarding hydrogen-fuelled vessels and related fuel cell systems are lacking. | L, K |
| *2b* | Detailed and prescriptive requirements for storage (including swappable systems/containers) and provisions for bunkering gaseous & liquid hydrogen (bunker station shipside etc.) are missing. | L, K |
| | *Central Commission for Navigation on the Rhine* | |
| *3* | Regulations for the use of hydrogen as a fuel on board inland navigation vessels are lacking. Hydrogen fuelled vessels are currently not allowed to operate on inland EU waterways. An exemption statement is required that can be requested at national authorities or the CCNR, depending on the operating area.<br>Special requirements of the CCNR are to be observed if an inland vessel will be operating in EU inland waters. RPR contains instructions aimed at conventional fuel bunkering but does not cover the possibility of bunkering hydrogen. Bunkering of hydrogen on inland waterways controlled by CCNR is currently not allowed. | L |
| | *Legislation in the Netherlands* | |
| *4a* | Bunkering of hydrogen on inland waterways in the Netherlands is currently not allowed. Exemptions could be made possible based on special permissions from the competent authority. | L |
| *4b* | "Basisnet", a nationwide appointed network for the transportation of dangerous goods, does not consider transportation of hydrogen in bulk. It must be noted that there are no limits for the transport of (mobile) tank-containers on waterways in Basisnet because the associated transport risk is considered to be very low. The probability of a leak in a container is very small that it will not contribute to the external safety risks /8/. This seems to imply that there will be | L, K |



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| | | |
|---|---|---|
| | no limits applicable for the transport of swappable hydrogen tubecontainers on waterways with container vessels to container terminals. | |
| | | *Legislation in Germany* |
| *5* | Bunkering of hydrogen on inland waterways in Germany is currently not allowed. Exemptions could be made possible based on special permissions from the competent authority. | L |
| | | *Port and harbour regulations* |
| *6a* | Specific rules and regulations for hydrogen liquid tankers (including bunker vessels), hydrogen-fuelled vessels and hydrogen bunkering activities (truck-to-ship & ship-to-ship) are lacking the port bye-laws of EU Ports & Harbours. | L, K |
| *6b* | Audit & Accreditation criteria for hydrogen bunker operators do not exist. | L, K |
| | | *Bunkering* |
| *7* | Rules for bunkering liquid hydrogen do not exist for the shipside of the bunker process. | L, H, K |
| *8* | Bunkering procedures & checklists for liquid hydrogen do not exist. | L, H, K |
| *9* | International standards for hydrogen refuelling points and bunkering for maritime and inland vessels do not exist. | L, H, K |
| *10* | Bunkering procedures & checklists for gaseous hydrogen do not exist. | L, H, K |
| *11* | An EU harmonized approach for risk assessment (including criteria) for non-Seveso hydrogen small scale establishments and bunkering activities (e.g. truck-to-ship, ship-to-ship) is lacking. | L, H |
| *12* | Indicators for determining common operational safety distances for hydrogen bunkering are currently missing. | L, H |
| *13* | Safety requirements for simultaneous hydrogen bunkering and loading / unloading or passenger embarking / disembarking processes are missing. | L, H, K |
| | | *On-board storage* |
| *14* | Qualification for (swappable & fixed) on-board storage pressure tanks with compressed hydrogen gas is lacking. Rules and requirements for use of swappable containers on board ships do not exist. | L, H, K |
| *15* | There is a lack of understanding of failure modes for liquid hydrogen tanks. | K |
| | | *Fuel cell system* |
| *16* | There is insufficient understanding of the safety aspects concerning release of hydrogen within the fuel cell system. | L, H, K |
| *17* | Ventilation requirements for fuel cell rooms are not validated for hydrogen. | L, H, K |
| *18* | Fuel cells open for new arrangement and vessel design solutions challenge existing rules & regulations. | L, K |
| *19* | Knowledge basis for requirements for handling of liquid hydrogen in piping to fuel cell system is lacking. | L, K |
| | | *Ship life phases* |
| *20* | There is a lack of best practices, procedures, codes or similar regarding safe handling of on-board hydrogen and fuel cell installations in all the life phases of a ship. Crew training requirements for use of hydrogen in shipping do not exist. | L, H |
| | | *Hydrogen safety* |
| *21* | There is insufficient understanding of hydrogen safety aspects for rules development. | L, K |
| *22* | There is a lack of understanding of properties and conditions affecting safety of liquid hydrogen in shipping applications. | L, K |

## 2.2 Land-based regulation and standards

The regulations for the land-based systems and infrastructure were also addressed in the study of DNV (2021d). It includes the construction, operation and permitting of bunker stations and the swapping of containers at container terminals. The relevant national legislation and standards in the Netherlands and Germany are also taken into account in this assessment.

### 2.2.1 Netherlands

In the assessment of the regulation in the Netherlands, there are different gaps identified, as shown in table 6. In this gap analysis, the identified gaps in the existing laws are also verified with the new Environmental Law (Omgevingswet) and related new decrees (replacing e.g. Bevi), expected to come into force in 2022.

*Table 6: Overview of identified gaps in the regulation in the Netherlands with the gap categories Legal (L), Harmonisation (H) and Knowledge (K) (DNV, 2021d)*

| Gap no. | Gap description | Gap category |
|---|---|---|
| | | *PGS guidelines* |
| 23 | A PGS guideline for the safe design and operation of a hydrogen bunker station is missing. | L, K |
| 24 | Guidelines for maintenance and repairing hydrogen fuel engines / fuel cell systems on inland vessels are missing in PGS 26. | L, K |
| | | *Bevi* |
| 25 | Small-scale hydrogen bunker stations (less than 5 ton storage, Brzo lower-tier threshold) & truck-to-ship bunkering is currently not regulated by Bevi / Bkl as they are not defined as categorial establishments / activities. | L, H |
| | | *QRA calculation guidelines* |
| 26 | A specific QRA calculation guideline for hydrogen bunker stations is missing. | L, H |
| 27 | The QRA calculation guideline for container terminals is included in the Reference Manual /9/, module C, chapter 5 does not seem to specify failure scenarios for compressed hydrogen tube-containers nor containers with cylinders. | L, H |

### 2.2.2 Germany

A similar assessment of the national regulation in Germany can be seen in table 7.

*Table 7: Overview of identified gaps in the regulation in Germany with the gap categories Legal (L), Harmonisation (H) and Knowledge (K) (DNV, 2021d)*

| Gap no. | Gap description | Gap category |
|---|---|---|
| | | *BImSchG / BauG* |
| 28 | BImSchG is missing adequate treatment of hydrogen (e.g. a specific hydrogen related BImSchV). | L |
| | | *12. BImSchV* |
| 29 | 12. BImSchV does not provide adequate treatment of hazards due to very low temperature or very high pressure hydrogen. | L |
| 30 | Technical details providing TRBS guidance for the specific hazards of hydrogen and hydrogen bunkering installations or stations for vessels are missing | L, K |
| | | *BetrSichV* |
| 31 | Treatment of the specific hazards of liquid hydrogen in the BetrSichV and in the associated TRBS are missing. | L, K |
| | | *KAS-18 ('TA Abstand)* |
| 32 | A technical guideline for definition of safety distances ('TA Abstand') is missing (hazards of hydrogen should be taken into account). | L, K |

## 2.3 Safety distances

Safety distances are established to prevent and limit the threat of hazardous consequences of possible major accidents. The Seveso III directive is the European legislation for control of major accident hazards, which have been implemented in different ways in the Netherlands (risk-based approach) and Germany (deterministic approach with implicit judgment of risk). There are a few bunkering scenarios assessed, which includes not only the short-term scenarios of bunkering pressurised hydrogen (swapping containers under 1; TTS or BTS bunkering under 2), but also the TTS bunkering of liquid hydrogen (3), ammonia (4) and methanol (5). There is a difference in the zoning: Zones resulting from the external safety distances in the Netherlands must be free of vulnerable objects (e.g. housing in residential areas, hospitals). Objects with limited vulnerability (e.g. isolated housing, small office buildings) can only be allowed to be present in the zone if it is sufficiently motivated. In Germany, it should not be understood as areas free of buildings. Within these zones less sensitive areas/usages (other than those described in BImSchG - article 50), this can be determined using KAS-18.



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*Table 8: Safety distances for different scenarios in the Netherlands and Germany (DNV, 2021e)*

| ***Scenario*** | **Description** | **External safety distance (in m)** | |
|---|---|---|---|
| | | The Netherlands | Germany |
| *1a* | Swapping containers with pressurised hydrogen (300 bar) at container terminals (start-up case) – no storage in stack | 39 | 182 |
| *1b* | Swapping containers with pressurised hydrogen (500 bar) at container terminals (future case) – storage in stack | 129 | 230 |
| *2a* | Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case) | 37 | 96 |
| *2b* | Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case) | 106 | 96 |
| *3* | Truck-to-ship bunkering of liquid hydrogen | 82 | 70 |
| *4a* | Truck-to-ship bunkering of refrigerated liquid ammonia | 175 | 205 |
| *4b* | Truck-to-ship bunkering of pressurised liquid ammonia | 543 | 395 |
| *5* | Truck-to-ship bunkering of methanol | 79 | 67 |

Main conclusion is that the safety distance of the 1a scenario (swapping containers without storage) is relatively small in the Netherlands, while larger in Germany (almost factor two compared to bunkering via hose). If there are hydrogen containers in stock, the safety distance becomes three times larger in the Netherlands, which isn't expected to be a problem for container terminals. The large distances for pressurised ammonia makes it challenging to introduce ammonia as a fuel in IWT.

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# 3. Design study

The design study had been performed partly simultaneously with the activities of the regulatory and safety analysis. In this chapter, the design is focussed on the short-term scenario of using swappable containers with compressed hydrogen. The design study includes an analysis of the technical equipment and gaps for this concept of bunkering hydrogen in swappable containers, a cost-benefit analysis and a blueprint for the filling station. The results described below can be found in the report of ZBT & EE (2021), unless referred otherwise.

## 3.1 Technical requirements

In this study, the technical requirements for the concept of bunkering hydrogen with the use of swappable containers have been identified. In this section, the technical requirements for each of the steps of the bunkering process are given.

### 3.1.1 Supply and bunkering process

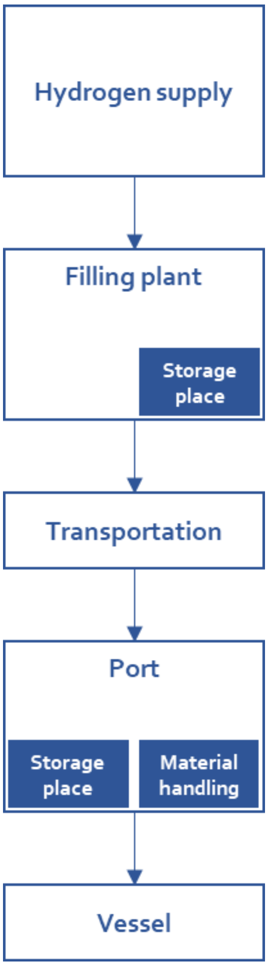


*Figure 6: Steps bunkering process (ZBT & EE, 2021)*

In the case of swappable containers, the process of supplying hydrogen to and filling of the hydrogen containers is schematically given in figure 6.

The first activity is the production of hydrogen, which can be done in several ways [2], currently mostly done by steam reforming of natural gas. However, carbon capture is needed to avoid $CO_2$ emissions ('blue hydrogen'). It can also be produced as a industrial by-product (by chlorine-alkali electrolysis). However, the highest potential for producing 'green hydrogen' is electrolysing with the use of solar or wind power.

Preferably, to avoid transportation costs, the hydrogen is generated onsite in a combination with a filling plant. If this isn't possible, there are several ways to transport hydrogen to the filling plant:

- Compressed hydrogen by pipelines.
- Liquid hydrogen in trucks or train.
- Stored in and transported in hydrogen carriers (same as the methods described under 1.1.3).

### 3.1.2 Filling plant

The filling plant consists of a hydrogen treatment unit depending on the kind of hydrogen supply, cleaning and drying can be needed. The study of ZBT & EE assumed the provision of dry hydrogen under maximum 30 bar. The next step is one or more buffers to control the inflow of hydrogen and to deal with possible pressure fluctuations. One or more compressors are needed to compress the hydrogen to the desired pressure. Furthermore, a filling device, piping, valves and the measurement and control technology are needed.

The filled containers can be stored on the same location of the filling plant. On this location, equipment (e.g. reach stacker) is needed to handle the containers and to load them on a trailer (or a vessel) for transport to the port.

### 3.1.2 Swappable containers

Assuming the use of swappable containers with compressed hydrogen, there are several choices in types of containers and the storage cylinders: The type of storage cylinders, the size of the container and the pressure of the hydrogen. The size of the container is most likely either 20ft or 40ft containers, as these are also the most used sizes for cargo containers. The type of storage cylinder and the choice of pressure are interdependent, most likely used combinations are 300 bar compressed hydrogen in type II cylinders (i.e. steel or aluminium partly wrapped with carbon fibre) or 300 or 500 bar compressed hydrogen in type IV cylinders

[2] A detailed overview of low-carbon methods of producing hydrogen is given in e.g. McWilliams & Zachmann (2021), Navigating through hydrogen. Bruegel, Brussels. https://www.bruegel.org/wp-content/uploads/2021/03/PC-08-2021_.pdf



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(i.e. composite of polymer liner and fully wrapped with carbon fibre). In table 9, the characteristics of these three combinations are given for a 20ft container.

*Table 9: Data sheet for a 20ft container with three cylinder type - hydrogen pressure combinations (ZBT & EE, 2021)*

| ***Specifications for 20ft container [unit]*** | **300 bar** | **300 bar** | **500 bar** |
|---|---|---|---|
| *Storage system* | MEGC | MEGC | MEGC |
| *Cylinder type* | Type II | Type IV | Type IV |
| *Dimensions [mm]* | 6058 x 2550 x 2550 | 6058 x 2432 x 2743 | 6058 x 2438 x 2700 |
| *Cylinders* | n/a | 54 | 48 |
| *Storage capacity [kg $H_2$]* | 312 | 371 | 518 |
| *Volumetric content [l]* | 15 912 | 18 900 | 16 800 |
| *Weight (empty) [kg]* | 21 000 | 9 250 | 14 000 |
| *Cost [*€1.000]* | 150 | 250 | 380 |

The decision for using a 20ft or 40ft containers, the cylinder type and pressure depends on the preferences of a ship-owning company, in BCI et al. (2021) flexibility, (operational) costs, ship conditions and operational profile are mentioned as deciding factors.

### 3.1.3 Technological gaps

Based on the technological requirements, ZBT and EE identified the technological gaps. In the storage in and the transportation of the containers, there aren't any real technical gaps. However, there are improvements desired in terms of weight and costs. The most complex of this bunkering process is the filling plant, which is currently mainly designed for filling Type I 200 and 300 bar bottles and bundles. Especially if chosen for 500 bar containers (with Type IV cylinders), there are restrictions in maximum filling rates and temperatures. The components of the filling plant are technologically mature, but the whole plant design is a challenge. Besides, the whole concept of the filling procedure with the buffers and compressors needs to be optimised.

## 3.2 Cost-benefit analysis

ZBT and EE (2021) analysed the costs and benefits. There are several operational cost components, in line with the process described under 3.1.1. An in-depth analysis is given in the report of ZBT and EE. They assessed two scenarios: The first ('small') scenario is the hydrogen generation by the use of 3 MW water electrolysis with 8 000 load hours for one vessel and a filling plant with one compressor. The second ('large') scenario involves 12 MW water electrolysis with 8 000 load hours for five vessels and a filling plant with four compressors. The cost components for H2 for the latter case are:

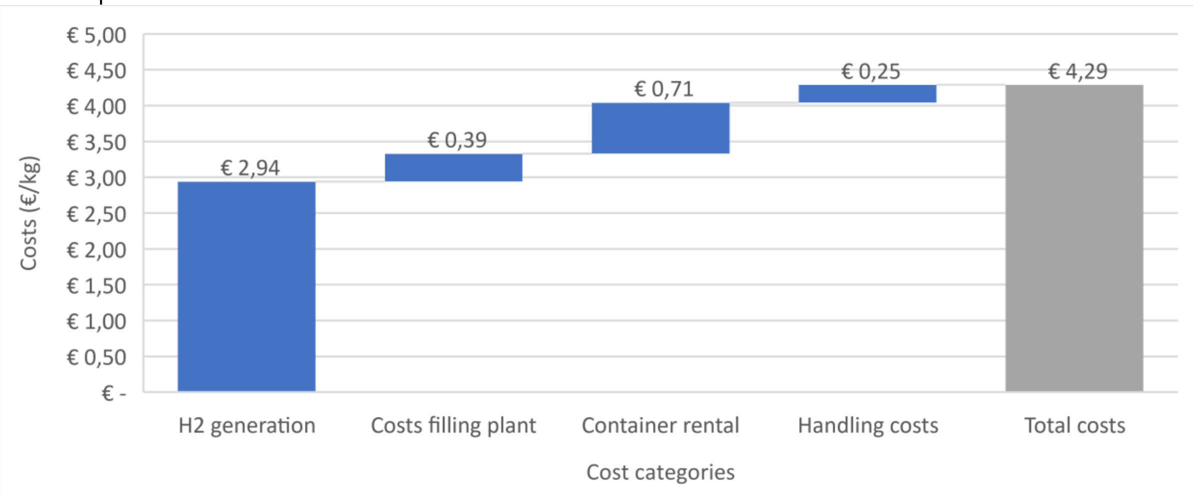


*Figure 7: Cost structure of hydrogen price (in €/kg) (ZBT & EE, 2021)*

In this analysis, ZBT and EE also assessed a third scenario, in which there is a 40% subsidy on CAPEX. The case of an average 135m container vessel navigating between Rotterdam and Duisburg is used for the further elaboration of the CBA. Based on this cost structure and assuming the annual number of roundtrips and the energy demand/fuel consumption per roundtrip, the fuel costs per year have been calculated for the three above-mentioned hydrogen scenarios and the current diesel scenario.


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*Table 10: Annual fuel costs for the case of an average 135m container vessel operating between Rotterdam and Duisburg (ZBT & EE, 2021)*

| ***Route/fuel*** | **Fuel consumption/ roundtrip** | **€/l or €/kg** | **Fuel costs/ roundtrip** | **Roundtrips/ year** | **Fuel costs/year** |
|---|---|---|---|---|---|
| *Diesel* | 15 459 litre | € 0,64 | € 9 894 | 144 | € 1 424 701 |
| *H2 (small filling plant)* | 2 746 kg | € 4,30 | € 11 808 | 144 | € 1 700 323 |
| *H2 (large filling plant)* | 2 746 kg | € 4,29 | € 11 780 | 144 | € 1 686 369 |
| *H2 (large filling plant + 40% CAPEX subsidy)* | 2 746 kg | € 3,70 | € 10 160 | 144 | € 1 463 069 |

The overview with annual fuel costs shows an increase of the fuel costs with somewhat more than € 250 000 in the non-subsidy hydrogen scenarios compared to the diesel scenario. Only in a scenario with 40% CAPEX subsidy, there is a minor increase in fuel costs.

In the cost-benefit analysis, also the other costs have been examined, including the social costs of emissions. In this analysis, besides the fuel costs, the depreciation and maintenance of the hardware (hull, engine, electrical system and fuel cells) and the financing costs are included. The social costs of emissions include the costs for CO2, NOx and PM. There are two diesel scenarios with different CO2 prices (respectively € 0,195 per kg and € 0,68 per kg), the 'regular' hydrogen scenario with a large filling plant and a scenario with 40% CAPEX subsidy (also on the investments of the vessel).

Figure 7 shows the different cost components for each of these scenarios, split in the financial costs (in blue) and the social costs (in black/grey). It shows clearly that besides the fuel costs, which is the largest financial cost component, also the other cost components (maintenance, depreciation, financing) are a factor three higher (without CAPEX subsidy) than for the diesel scenario. Without CAPEX subsidy, the total annual (financial) costs are around € 500 000 higher for a hydrogen vessel than for a diesel vessel. However, ZBT and EE assume that the external costs for $CO_2$, $NO_x$ and PM are € 1.9 million in the low CO2 cost scenario.

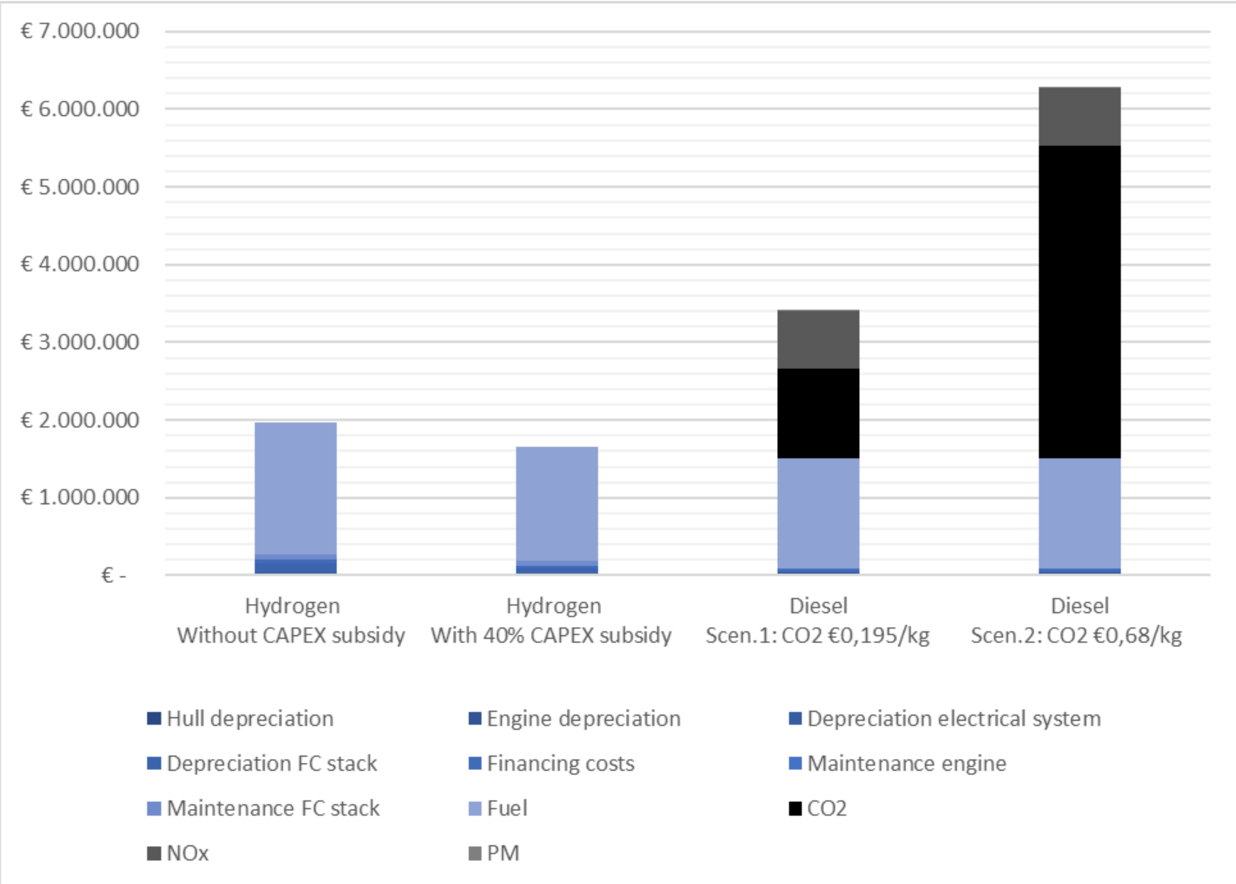


*Figure 8: Costs per vessel per year with in blue the financial cost components and in black/grey the external cost components (based on ZBT & EE, 2021)*


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The CBA for this case shows the main paradox for the implementation of hydrogen, i.e. a hydrogen vessel has higher operational costs compared to a similar diesel vessel, while the external costs for a vessel with an ICE operating on fossil diesel are higher. Unless the external costs are internalised (in either taxation or incentives), there is a negative business case for a hydrogen vessel. In the RH2INE programme (as the global project of this action), the costs and benefits will also be calculated for some more cases of inland vessels. It is important to include these calculations, as operational profiles – and thus energy demand – for specific inland vessel can vary. An update is also needed for the outcomes of the different cost components.



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# 4. Location Study

The last technical study of the RH2INE Kickstart Study was the location study. In the location study, the location requirements, spatial demands, the demand per port and the investment have been assessed. The results described below can be found in the reports of BCI, CE and KIWA (2021), unless referred otherwise.

## 4.1 Location requirements and spatial demands

For the location requirements, three types of locations have been taken into account:
- Existing container terminals
- Existing (dry) bulk terminals
- Green field locations

The most feasible location for the swapping of the hydrogen containers is at an existing container terminals. Most container terminals are capable of handling dangerous goods and the equipment (e.g. cranes) and infrastructure to store and handle tube containers are available. Furthermore, it makes it possible to include the swapping of hydrogen containers in the vessel's operations. There are sufficient number of terminals in the three ports involved in the Kickstart Study to facilitate the expected demand. Because each individual container and dry bulk vessel operator has its own customers, destinations, routes and therefore their own logistic process in the long run a broad coverage of possible swapping locations is needed and also green field locations and bulk terminals need to be developed and used. However, in these cases, there are safety requirements needed (e.g. safety distances, such as given under section 2.3).

## 4.2 Demand

The spatial demand is also based on the expected demand for hydrogen in the different ports. Based on the vessel passages, the ports of origin and destination and the energy demand, BCI et al. made an assumption concerning the expected share by each of the port areas in the total hydrogen demand by inland vessels, as can be seen in figure 9.

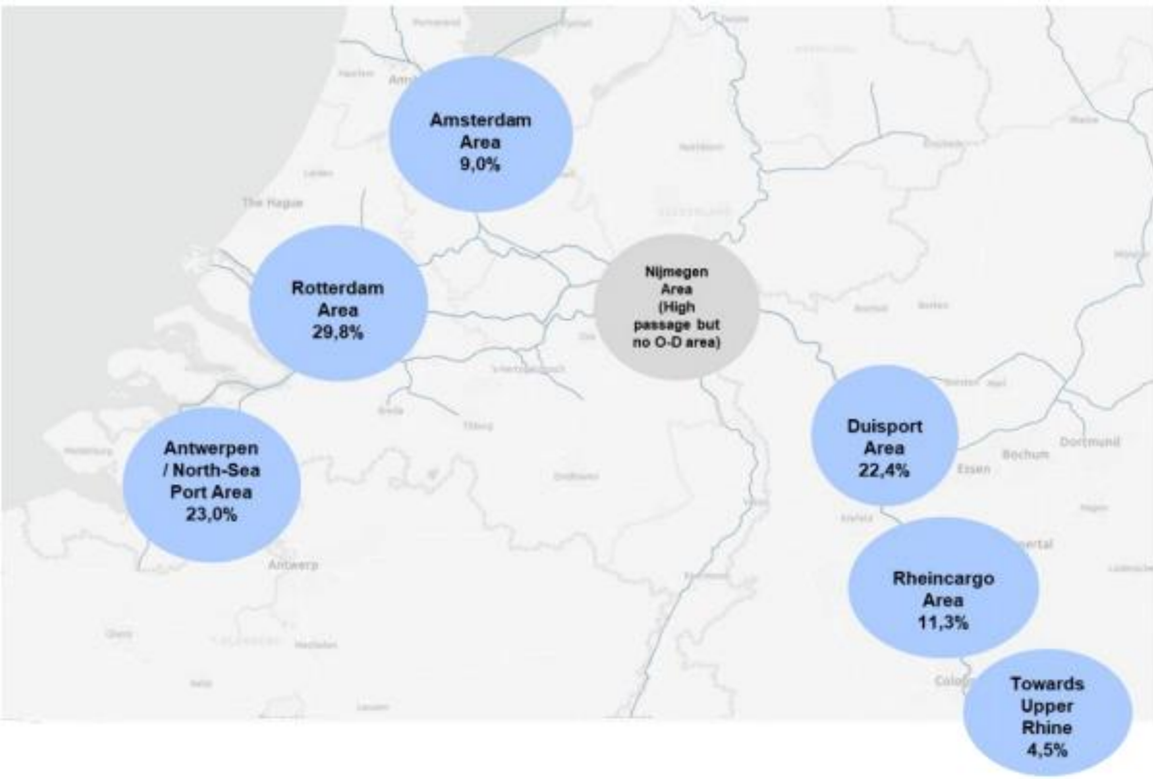



*Figure 9: Projected share in demand for hydrogen per port area (BCI, CE & KIWA, 2021)*

The projected share can be affected by several factors, such as the logistics and the number of hydrogen vessels, the hydrogen supply, market and price developments for each of these ports. For example, a strategy

with less hydrogen containers onboard and more stops can result in a demand in intermediate ports (e.g. Nijmegen).
Based on the projected share, BCI et al. calculated the expected demand in the three demand scenarios (as given under 1.4) for 2030 and 2040. The total demand in the Rhine area and split in the demand per port area is given in figure 10. In the low scenario, the total hydrogen demand is 5 000 tonnes in 2030 (10 000 tonnes in 2040), of which 1 490 in the Rotterdam area, 1 120 in the Duisburg area and 565 tonnes in the area of the RheinCargo ports. In the high scenario, the total hydrogen demand is 48 000 tonnes in 2030 (104 000 tonnes in 2040), of which 14 304 in the Rotterdam area, 10 752 tonnes in the Duisburg area and 5 425 tonnes in the RheinCargo area.

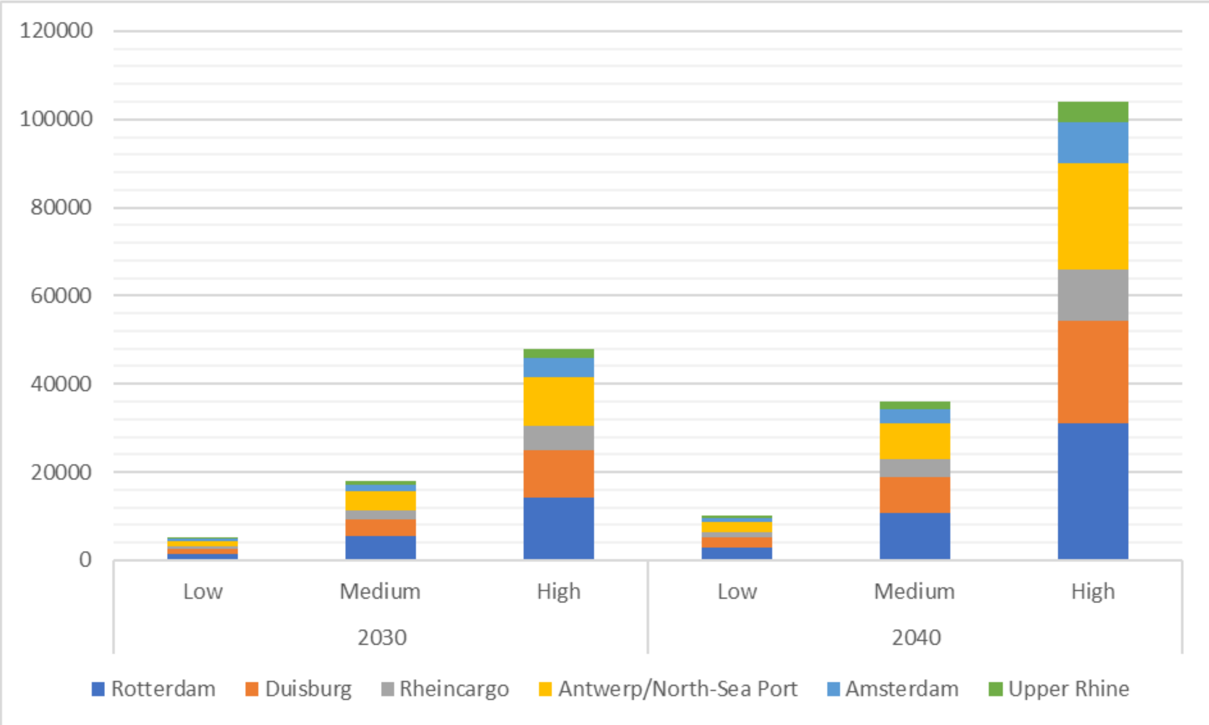
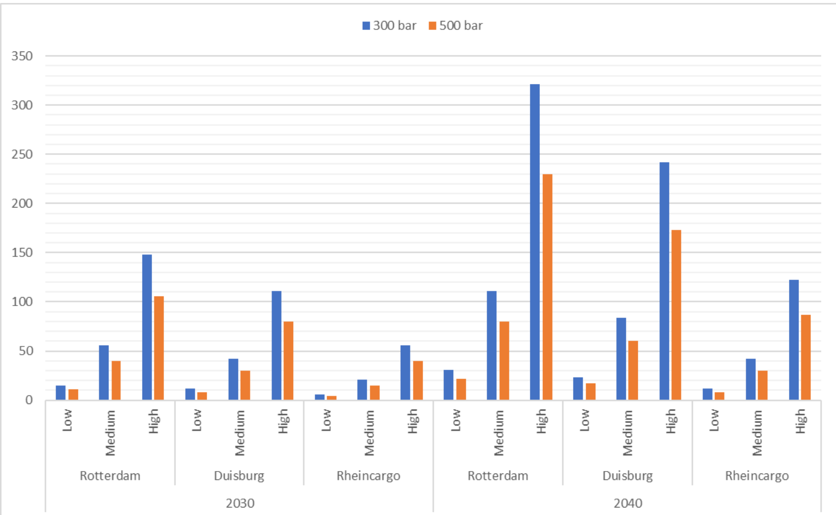



*Figure 10: Projected hydrogen demand in different scenarios and in the various port areas in 2030 and 2040 (BCI et al., 2021)*




The hydrogen demand can also be used to calculate the number of filled hydrogen containers needed per port area per day. This expectation is given in figure 11. In 2030, assuming 300 bar containers, there are daily 148 filled containers in a high scenario (15 in low scenario) needed in the Rotterdam area, and 111 (12) in Duisburg and 56 (6) in RheinCargo.

*Figure 11: Number of filled $H_2$ containers needed per port area per day (BCI et al., 2021)*



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## 4.3 Investments needed

In their analysis, BCI, CE and KIWA also assessed in a qualitative way the various cost elements of the value chain. Already mentioned in the study of ZBT and EE, a substantial additional investment is needed in the vessel to be able to sail on hydrogen, like for the fuel cel, the safety systems and the hydrogen containers. Also the operational costs are higher mainly caused by the cost of green hydrogen and the handling costs of the hydrogen containers.

On the shore side in the short-term it is expected that the swapping of hydrogen containers in the three ports can be done at existing container terminals, so investments on the shore are in this phase mainly needed for the filling solutions and the logistics. Because of the relatively high road transport costs for H2-containers, locations close to container filling stations are desirable. In the study it is mentioned that hydrogen producers are willing to invest in filling stations and container systems, but due to the small scale of container swapping, some investors are likely to wait for fixed tanks and hose bunkering options. In the long run investments are needed in a broad coverage of possible swapping locations to serve the different operator profiles.

For the phase of upscaling the fleet there are important economics of scale achievable in the number of containers that are needed. In this phase a more centralized container solution is desirable, with preferable a pay for use concept. Also then a scaling up is needed for the container logistics to guarantee higher frequency of transport to container terminals and also higher filling speed at filling stations are needed.

## 4.4 Mid- and long-term scenarios

In the design study and the location study, also the mid-term scenario of liquid hydrogen and the long-term scenario of hydrogen carriers have been assessed in a qualitative way. The design study concludes that liquid hydrogen can be bunkered in two ways in the future, stored in swappable insulated tank containers or bunkered from shore, by a bunker barge or truck. Especially in scaling up, and also because of the possible safety issues of liquid hydrogen stored in containers, the bunkering of fixed installations seems more viable for newly built vessels (with containerised systems possibly still to be used for existing vessels). Both require the development of distribution systems, as liquid hydrogen will most likely produced centrally in liquefaction plant or imported. The possible transition on the mid term towards bunkering doesn't make it likely that dry bulk terminals are willing invest in equipment for swapping hydrogen containers. The various hydrogen carriers – identified as long-term solutions – require onboard adaptations in equipment and storage. Main advantage for LOHC, methanol and $NaBH_4$ is that they can be easily transported.


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# 5. Conclusions and recommendations for the roll-out

The objective of the RH2INE Kickstart Study is to support the regional and port authorities in gaining insight into the requirements for the implementation of hydrogen (infrastructure) for inland waterway transport. The previous chapters of this roll-out plan summarised the outcomes of the studies on scenarios, safety and regulatory framework, design and location. In this last chapter, the conclusions and recommendations are addressed, aspects that have to be covered or are needed to come to the implementation of hydrogen infrastructure and aspects needed for the further roll-out of these outcomes.

Within the RH2INE programme, market operators, mainly the ship-owning companies, already done private research and are applying for funds for additional and complementary studies. Ship-owning companies investigate drivetrain and storage solutions. This involves applied research in different programmes. The outcomes of the RH2INE Kickstart Study will be used in the next steps in a value chain approach of the supply and demand of clean hydrogen by IWT to come to the realization and operation of hydrogen propelled ships and the needed infrastructure on the shoreside.

## 5.1 Conclusions on the outcomes of the Kickstart Study

Before introducing the recommendations for the implementation and roll-out, it's helpful to start with shortly summarising the main outcomes of this study. The study clearly identified a transition path of implementing hydrogen on the short, mid and long term, which is justified by a zero-emission transition approach and therefore by the requirements in each of these stages and the advancing of (currently still immature) technologies.

**The main conclusion is to focus on technologically mature solutions with the use of flexible, modular storage and bunkering concepts on the short term and more efficient – especially in energy density – solutions on the longer term.** There are also clear ideas on the bunkering and logistical process of filling, transporting and swapping hydrogen containers, and the implications of this process on the safety aspects. As can be expected in this first stage of implementing hydrogen, there are still some outstanding topics worth being mentioned.

***The RH2INE "blue print kickstart" hydrogen in IWT: Modularity and flexibility as no-regrets strategy***

The short-term solution consists of swappable containers with pressurized hydrogen, as is widely available, technologically mature and providing flexibility to the port operator as well as the ship-owner. For the ship-owner, the bunkering by swapping containers provides a relatively quick fuelling solution. For the port operator, it provides flexibility in limited space requirements, only minor implications for the safety requirements and avoiding high investments. The last aspect also results in limiting the risk of stranded assets, if in the future other forms of hydrogen would be used.

In the supply process, the preferable situation is to have hydrogen generation (by water electrolysis) on-site on one location with a filling plant, that can also be used for other purposes (e.g. as tank location for hydrogen vehicles). This filling plant is preferably on short distance of the ports, making it possible to refill empty hydrogen containers and transport them to the container terminals in a short period of time and without having (too much) hydrogen containers stored on the terminal. This is also important for the safety distances. Existing container terminals in the three ports are in the short term the preferable swapping locations, as it is already possible to handle the hydrogen containers there.

In the mid- and long-term scenarios, liquid hydrogen and hydrogen carriers are expected to become more preferable. This also causes changes in the process of bunkering, for example by using ships or bunker stations, with higher investments needed to build them. Furthermore, this can also result in a changing supply chain and changes on-board of vessels. The use of the modular container systems limit the impact of the changes on-board of existing hydrogen fuelled vessels.



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***Outstanding topics: standardisation, regulatory gaps, logistical process***

The first inland vessels with a hydrogen fuelled propulsion which are used for regular cargo transport are under development and the first vessel is expected to come in operation in 2022. A major benefit of the process within RH2INE and especially the close involvement of stakeholders is that it became clear – as mentioned above – that there's a clear preference for the solution of swapping containers, at least on the short and mid term. However, in this stage of development, there are still some outstanding topics. These topics should be taken into account in the implementation of hydrogen in IWT and should be covered in case of further scaling up.

Currently, there are variations in the preferences among ship-owning companies regarding the pressure of the hydrogen (300 or 500 bar), type of cylinders (Type II-IV) and containers (20 or 40 ft). The operational profile and logistical process are determining factors for these preferences. However, in the design as well as in the location study, it was concluded that a standardised solution would be preferable (especially in the scale-up). In the first stage of implementing hydrogen, it is acceptable that each of these variations are used and tested. To be prepared for further scaling-up, it is needed to investigate whether these solutions are exchangeable or can be used for different segments, and to what degree standardisation of these solutions are needed.
The study of DNV identified the safety distances for the various scenarios of bunkering and storing hydrogen. This study also concluded the gaps in the current regulation. They proposed some solutions to overcome these gaps. The first inland vessels operating on hydrogen need an exemption from the CCNR to use hydrogen. These first demonstrations are required to be assessed closely on the safety aspects and will be used in the implementation of regulation and safety guidelines. In this process, advantage can be taken of former processes for implementing the storage, bunkering and use of alternative fuels (e.g. LNG) in regulations.

The logistical aspect of the swapping of container is an important factor in the efficiency of this concept. In the CBA of ZBT and EE, the renting of the container contributes 16.5% to the fuel costs. Currently, each of the ship-owning companies makes arrangements with its hydrogen supplier on the number and supply of containers. For the phase of upscaling the fleet there are important economics of scale achievable in the number of containers that are needed. In this phase a more centralized container solution is desirable, with preferable a pay for use concept. Also then a scaling up is needed for the container logistics to guarantee higher frequency of transport to container terminals and also higher filling speed at filling stations are needed. In the long run a broad coverage of possible swapping locations is needed.

***Funding needed on the shore side in the first phase kickstarting the transition towards zero-emission by using hydrogen in IWT***

In the short-term scenario of swapping hydrogen containers at existing container terminal in the three ports, there is already equipment available for the handling of the containers, even with dangerous goods.

Funding is needed for the investments in the hydrogen containers. For the upscaling there are economics of scale achievable in the number of containers that are needed. In this phase a more centralized container solution is desirable, with preferable a pay for use concept. The market parties are already looking into developing new concepts, like those used with battery packed containers.

Investments are also needed in the ports for the filling stations; in a hydrogen treatment unit, storage, supply, cleaning, draying, safety, security and distribution. Next to this there are optimisations needed in the scaling-up to guarantee higher frequency of transport to container terminals and filling speed at filling stations.



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## 5.2 Further recommendations for the implementation roll-out next phases

In the RH2INE Kickstart Study, a few conditional aspects have been identified and should be taken into account in the implementation and roll-out of hydrogen in IWT this first phase and the phases to come.

***Corridor focussed approach***

RH2INE is initiated by public and private stakeholders along the corridor between Rotterdam and Cologne. As mentioned by EICB (2020), a corridor focussed approach is needed for the implementation of hydrogen in IWT. In this report, RH2INE is mentioned as an example of a corridor focussed approach. The focus is needed to kickstart the transition towards zero-emission use of hydrogen in IWT. To achieve the ambition of the RH2INE programme (a fit between the supply of clean hydrogen and its demand in transport), a standardisation on the entire Rhine(-Alpine) corridor is needed. As well as other TEN-T corridors. The location study already provided a short overview of the potential demand in other ports along the Rhine-Alpine corridor, such as Amsterdam, Antwerp and the Upper Rhine. Further research on the implementation of hydrogen on this corridor, in the context of the EGTC Rhine-Alpine is foreseen and could contribute to a further geographic expansion of the activities of RH2INE. Within the EGTC Rhine-Alpine a research has been started and will deliver an overview of hydrogen and transport activities along the Rhine-Alpine corridor by the end of 2021.

***Facilitation of market initiatives***

The decision for the implementation of hydrogen bunkering facilities in a port should always be motivated by the desire of a ship-owning company – supported by an IWT operator or a shipper – to build or retrofit an inland vessel with a zero-emission propulsion. Facilitating the market initiatives of ship-owning companies is the leading motive in decisions for specific bunkering methods and locations. It isn't a top-down approach, it is a market driven, cross-border, value chain and transition approach involving several stakeholders. The concept presented in the previous chapters – and summarised under 5.1 – is concluded as most feasible after consulting private and public stakeholders, especially companies already involved in developing hydrogen powered vessels. The demand scenarios for each of the ports are based on different aspects, such as the number of vessel passages, the operational profiles of these vessels and their energy demand.

***Cooperation along the value chain***

RH2INE is a value chain approach. The transition towards zero-emission and the implementation of hydrogen in IWT involves the cooperation of companies along the whole value chain. It requires the initiative of ship-owning companies (supported by their customers), but also the availability of (clean) hydrogen and maritime equipment. A close cooperation with hydrogen suppliers and other regions/ports is needed. The Letter of Intent of the RH2INE programme is signed by governmental organisations, port authorities and companies from the different sectors.

***Policy measures needed to improve business case***

Simultaneously to the Kickstart Study – a few ship-owning companies are in the process of developing, financing and building hydrogen fuelled inland vessels with non-conventional funds, including subsidies. The result from the business case calculations and costs benefit analyses so far conclude that hydrogen fuelled inland vessels have significantly higher costs than similar inland vessels operating with conventional ICEs on diesel. Besides the higher investment costs, the hydrogen price, the costs of H2 storage, transport and handling and the depreciation and financing of the equipment result in an increase in operational costs.

As transport is still mainly cost-driven, it is hard to pass these higher costs down the value chain to the customer. More important, there is a contradiction between higher investment and operational costs for the use of hydrogen in the current situation, while contributing to lower external costs (in reducing CO2 and air pollutant emissions). Policy measures are needed to internalise these externalities, for example by taxation and/or by providing incentives (in subsidies or discounts), thus improving the business case of the vessels and stimulate the demand for green hydrogen in each of the ports.



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