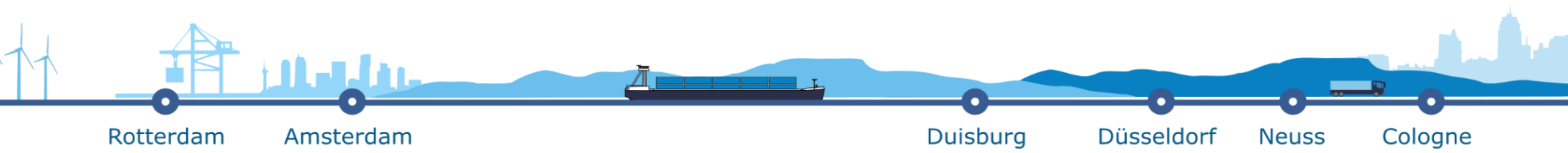
RH_2INE Kickstart Study

Location Study

RH_2INE

Rhine Hydrogen Integration Network of Excellence



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RH2INE location study

Final

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Abbreviations

ADN	European agreement for transport of dangerous substances through inland waterways
ADR	Agreement concerning the international carriage of dangerous goods by road.
ATEX	ATmosphere EXplosible
BAL	Besluit activiteiten leefomgeving
BimSchG	Bundes-Immissionsschutzgesetz
CH2	Compressed hydrogen
HRS	Hydrogen refilling station
H_2	Hydrogen
LCOE	Levelized cost of energy
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
LHV	Lower heating value
MeOH	Methanol
MEGC	Multi element gas container
RCS	Regulation, Codes and Standards
PGS	Publicatiereeks gevaarlijke stoffen
TCO	Total cost of ownership
TEU	Twenty feet equivalent unit
WACC	Weighted average cost of capital

Summary

This location study of the RH2INE kick-start study (Sub-study 3) focuses on the use of swapping compressed H_2-containers for the propulsion of inland waterway vessels. It provides a market view about the impact of the use of hydrogen containers in inland shipping and analyses possible locations where H_2-containers can be swapped from land to vessels and vice versa. This report is a follow-up of three previous sub-studies within the kick-start study (Sub-study 1a: Technical scenarios for ships and filling stations, Sub-study 1b: Safety and regulatory analysis and Sub-study 2: Design study). These studies concluded that:

- In the short term, bunkering will preferably be done with compressed hydrogen (CH2) in swappable containers with a pressure between 200 and 500 bar. *In our study we conclude that 20ft or 40ft 300 bar H_2 containers are expected to be the preferred option for the coming years*.
- In the medium term, bunkering will probably make use of liquid hydrogen (LH_2) in swappable containers, or consist of bunkering by hose. The use of liquid hydrogen is however primarily foreseen in niche markets such as cruise vessels and ferries and not in inland shipping. This is because of the high fuel price, limited added value in terms of total CO2 emission reduction, challenges regarding storage and continuous generation of boil-off gas and safety requirements.
- In the long –term, bunkering is foreseen to make use of hydrogen carriers, e.g., some hydrogen-based liquid fuels like LOHC or sodium borohydride (NaBH4). Non-cyclic fuels like ammonia and methanol are seen as more suitable for the maritime sector than other liquid hydrogen carriers, but these are less useful for inland shipping due to safety reasons. However, these types of carriers are still in the early stages of their development. There are still many uncertainties about their use and possibilities.

Based on these conclusions, it was decided that swapping compressed hydrogen (H_2) containers is seen as the most realistic option to be used by inland shipping in the foreseeable future.

The Demand study (sub –study 1.1c, DNV-GL) defined the following demand scenarios for the demand of inland waterway vessels on the Rhine corridor:

Table 1 Demand volume scenarios of the RH2INE demand study

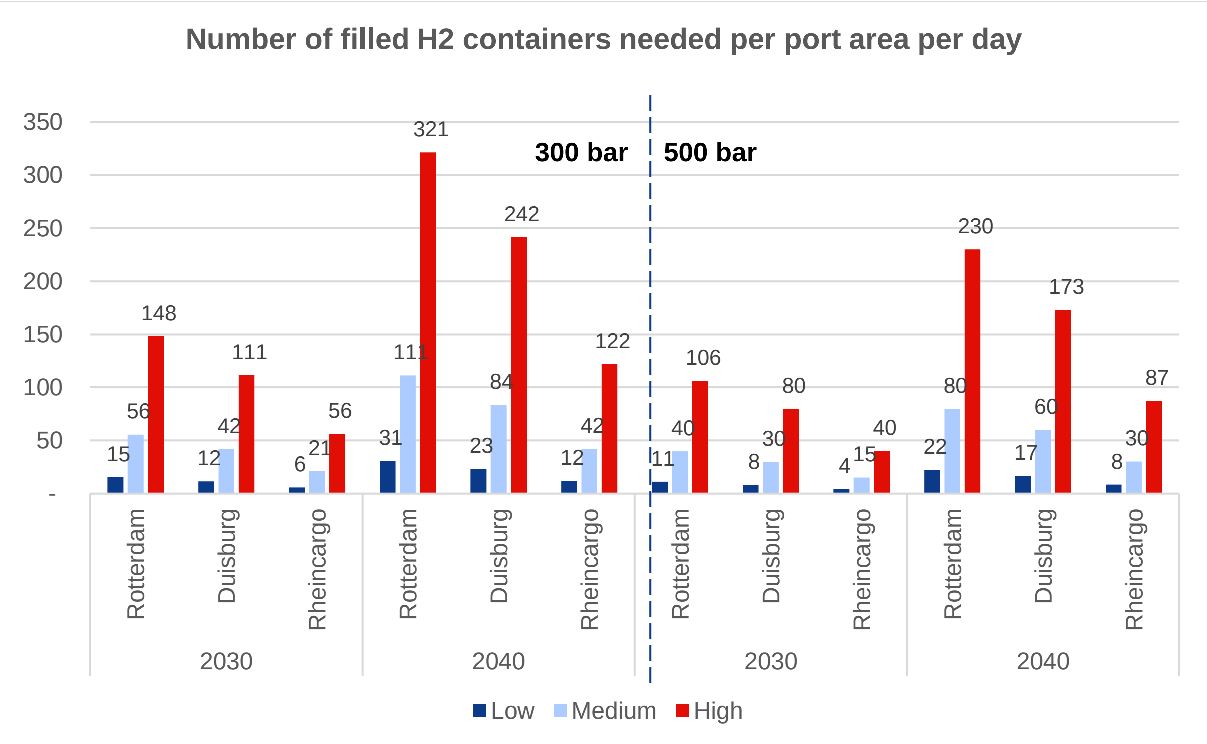
Year	Low (tons)	Medium (tons)	High (tons)
2030	5.000	18.000	48.000
2040	10.000	36.000	104.000

Vessels per day	Low (tons)		Medium (tons)		High (tons)	
Fuel consumption H_2 per round trip (tons)	1,8	2,8	1,8	2,8	1,8	2,8
2030	11	7	38	25	103	66
2040	21	14	77	49	222	143

Based on these scenarios, in 2030 the total number of filled hydrogen containers needed in the Rotterdam area is on average 11 to 148 containers per day (depending on the total demand and the pressure of the hydrogen (300 – 500 bar)). The demand in the Duisburg/Duisport area is 8 to 111 filled H_2 containers and in the RheinCargo area 4 to 56 filled H_2 containers. The projected number of vessels that demand hydrogen bunkering per day in the year 2030 is 2 to 31 for Rotterdam , 2 to 23 for Duisport, and 1 to 12 for RheinCargo. This demand is expected to be affected by:

- logistics strategies of ship owners and terminal operators;
- market developments in hydrogen supply volumes, locations, supply structures (e.g. shared pool of containers), which can lead to different cost structures in different locations and varying logistics costs;
- decisions based on financial grounds (actual costs of filled H_2 containers in different locations);
- resulting choices on the degree of investment in hydrogen swapping systems.

Figure 1 Number of filled hydrogen containers needed per port area per day (without spare containers)



Swapping H_2 containers is viable
A swappable compressed hydrogen container system is useful and viable as a short-/mid-term solution to initiate the use of hydrogen in inland shipping. There are, however, some hurdles that must be overcome before the concept of swappable containers becomes feasible.

The container handling infrastructure and organisations to swap containers are already available. In each port multiple container terminals already exist and are best suited to the location requirements to handle and swap H_2-containers. Most of these terminals are already handling containers with dangerous goods and are therefore allowed to handle hydrogen containers as well. The terminal organisations are also trained in handling dangerous goods and have the right permits. Furthermore, the capacity of these terminals is high enough to handle the H_2 containers now and in the future. *No additional investments are needed at (existing) container terminals which already handle dangerous goods*.

Hydrogen containers can be handled as any other dangerous goods containers. Therefore, *container swapping fits well with existing logistics operations of container terminals and inland shipping organisations.* Deep sea container terminals are, because of their scale and focus on maritime shipping not preferred locations. The smaller (inland) container terminals are more likely to be able to meet the requirements for container swapping. Dry bulk terminal organisations are not (yet) familiar with this system and are not equipped for this.

Because hydrogen is a dangerous good, safety requirements are necessary on site and licenses are needed. However, many container terminals already handle different dangerous goods including hydrogen. For these terminals the extra hydrogen containers will not have a substantial impact on their current procedures. The health/safety/environment requirements only allow temporary storage of H_2 containers. This has an effect on the logistical planning of the H_2-containers. The full containers must be delivered at the right time.

Challenges
To enable efficient operations while using H_2 containers and not to disrupt logistics too much, it is important that hydrogen containers are available at the moment they are needed by an inland vessel. The following conditions must be met:
1 Sufficient locations where H_2 containers can be swapped.
2 Sufficient available H_2 –containers at each swapping location.
3 Reasonable costs for using H_2 as fuel in inland shipping.

The first condition can be fulfilled, as many existing container terminals can swap the H_2-containers. This provides a wide range of locations, allowing every inland shipping organisation to choose the optimal location which suits its logistics (destinations, routes, etc).

To meet conditions 2 and 3, some challenges must be overcome:
- ***Development and scaling up number of available H_2 –containers:*** This requires large investments which must be made some time before sufficient turnover can be generated. It also requires standardization of the H_2 containers. (Technical) standardization makes the exchange and inspection of containers easier and flexible. Standardization requires good cooperation between all parties involved and perhaps also some frontrunners who take this up.

- ***Expansion of the number of H_2 vessels:*** The number of H_2 containers and the number of H_2 vessels depend on each other. An important cost item is the container rental/leasing cost. The larger the container market, the lower the cost per container. However, the number of H_2 containers are dependent on the need for these containers. Investment in the expansion of the number of H_2 vessels is therefore necessary.
- ***Cost of H_2:*** A good price for H_2 is important for the business case of vessel owners. Hydrogen is at this moment still an expensive fuel. It is important that the market of H_2 grows in volume and that the production costs fall sharply. Another operational cost aspect for the vessel operators is the cost of the containers swapping system. A cost-effective organization of the H_2 containers can have a positive influence on the costs. A container pooling system with standardized containers is probably most viable. The market party who invests in the compressed hydrogen containers owns the containers and is responsible for their proper functioning and safety of use (and takes care of certification and maintenance of the containers).

  A third cost aspect is the costs of the transport of H_2 containers from and to hydrogen filling stations. Filling stations and container terminals should therefore preferably be close to each other. However, filling stations will often be located near hydrogen production locations and should also be accessible to vehicles that refuel at the filling station.

Some hydrogen producers are willing to invest in filling stations and container systems. On the other hand, due to the expected small scale of container swapping, some investors will probably wait for fixed tanks and hose bunkering options, possibly because they are reluctant to invest due the risk of stranded assets.

Chapter 1 **Preface**

The Dutch government is strongly committed to the development of hydrogen (H_2) as a fuel for various modalities. This has been laid down, among other things, by the EU Green Deal and in the Dutch Climate Agreement. In extension, the implementation strategy for Hydrogen in Mobility (Ministry of Infrastructure and Water Management) contains an elaboration for the various modalities. For example, Dutch policy is aimed at having 20 filling stations by 2020, 15,000 hydrogen cars, 3,000 hydrogen commercial vehicles and 50 hydrogen filling stations in 2025, 300,000 hydrogen cars and 300 hydrogen filling stations in 2030. For inland shipping, one of the concrete initiatives to implement this, is the RH2INE programme[1].

The German government is strongly committed to the use of green hydrogen for the production of fuel and as an alternative to conventional types of fuel as well. The German government will therefore embed this into German law[2]. To stimulate the transition, Germany has funding programmes to boost investments in hydrogen-powered vehicles (light and heavy-duty vehicles, buses, trains, inland and coastal navigation, car fleets).

The Rhine Hydrogen Integration Network of Excellence (RH2INE programme) is an international European programme and consists of public and private parties. The aim of the programme is to implement hydrogen as a fuel in inland waterway transport. The RH2INE Kick start Study consortium consists of the following partners: Province of Zuid-Holland, Ministry of Economic Affairs, Innovation, Digitalisation and Energy of North Rhine-Westphalia, the Port of Rotterdam, Duisport and RheinCargo.

The key barriers for the implementation of hydrogen in inland shipping are the current scarcity of hydrogen-powered vessels and the lack of Hydrogen refilling stations (HRS), which is caused by multiple issues like high costs, regulatory issues, etc.. Several hydrogen and transport companies are however ready to invest, and are already investing, in hydrogen-powered vessels and in HRS. The RH2INE programme has the objective to join forces in this process and has therefore in 2020 initiated a kick-start study to prepare investments in at least three hydrogen fuelling stations, located in three core inland ports in Germany and The Netherlands, situated on the Rhine-Alpine corridor between Rotterdam and Cologne. The study exists of 4 cohesive sub-studies which together will lead to a strategic rollout plan. The sub-studies are:

- Sub-study 1a – Technical scenarios for ships and filling stations
- Sub-study 1b – Safety and regulatory analysis
- Sub-study 2 – Design study
- Sub-study 3 – Location study

[1] https://www.rh2ine.eu/
[2] See Bibliography nr 16.

The first three sub-studies have been finished and have delivered their final reports. Sub-studies 1A and 1B provided insight in technical scenarios and safety and regulations aspects of hydrogen inland vessels, fuelling stations and infrastructure. Result of sub-study 2 was a technical design of the fuelling locations and essential infrastructure. The current report is the result of sub-study 3: the location study. Based on the three sub-studies a strategic rollout plan will be made.

Figure 1.1 Example of possible bunker variant (source: Port of Rotterdam)

The original assignment for the location study was to make an analysis of the best choice of suitable locations in three ports (location in the ports Rotterdam, Duisburg and in Neuss/Cologne/Düsseldorf (RheinCargo ports)) for three bunker scenarios which should result from sub-study 1A and which also meet regulatory requirements. For these three locations, a strategy for expansion (including H_2-demand scenarios for the specific locations and an assessment of combined use of the H_2 fuelling stations by other modalities) and a Blueprint should be made. Based on the defined and weighted location requirements and spatial demands for the three bunker scenarios, the locations could be compared and assessed. For the most preferential hydrogen fuelling station an investment plan had to be made. During the course of the project however, it appeared that sub-study 1.1 b “Hydrogen bunkering scenarios” concluded that the foreseen bunkering scenarios are:

- Short term bunkering will be preferably done with compressed hydrogen (CH2) in swappable containers with pressure from 200 to 500 bar.
- Mid-term bunkering will be probably liquid hydrogen (LH2) in swappable containers or bunkering via hose. The use of liquid hydrogen is however primarily foreseen in niche markets such as cruise vessels and ferries and not in inland shipping. This is because of the high fuel price, limited added value in terms of total CO2 emission reduction, challenges regarding storage and continuous generation of boil-off gas and safety requirements.
- Long-term bunkering is seen with hydrogen carriers, e.g. some hydrogen based liquid fuels like LOHC or sodium borohydride (NaBH4). Non-cyclic fuels like Ammonia and Methanol are seen as more ready for the maritime sector than other liquid hydrogen carriers, but these are less useful for inland shipping due to safety reasons. However, these types of carriers are still in the early stages of their development. There are still many uncertainties about their use and possibilities.

Based on these conclusions, it was concluded during a workshop by the RH2INE consortium that, for now, swapping compressed hydrogen (H_2) containers is seen as the most realistic option to be used by inland shipping in the foreseeable future. All other techniques are still too uncertain and/or not suitable for inland shipping. Therefore, this location study focuses mainly on the use of swapping compressed H_2-containers and not on different bunker scenarios. At the final stage of this study, a qualitative analysis has been given of the impact that can occur when other hydrogen carriers are being used in inland shipping in the medium and, in particular, the longer term, which may lead to bunkering via hose.

Because of this scope change, no more analyses have been performed for suitable locations for different bunker scenarios, no different blueprints have been made and no specific investment plan was needed per bunker location. Instead, interviews[3] and discussions were held with market parties (barge organisations, terminal organisations and H_2 suppliers) about the more detailed requirements for the handling of H2-containers at terminals and the supply and removal of these H_2-containers and the use of H_2-containers in inland shipping. This report provides a view of the market about the impact parties expect of the use of hydrogen containers in inland shipping.

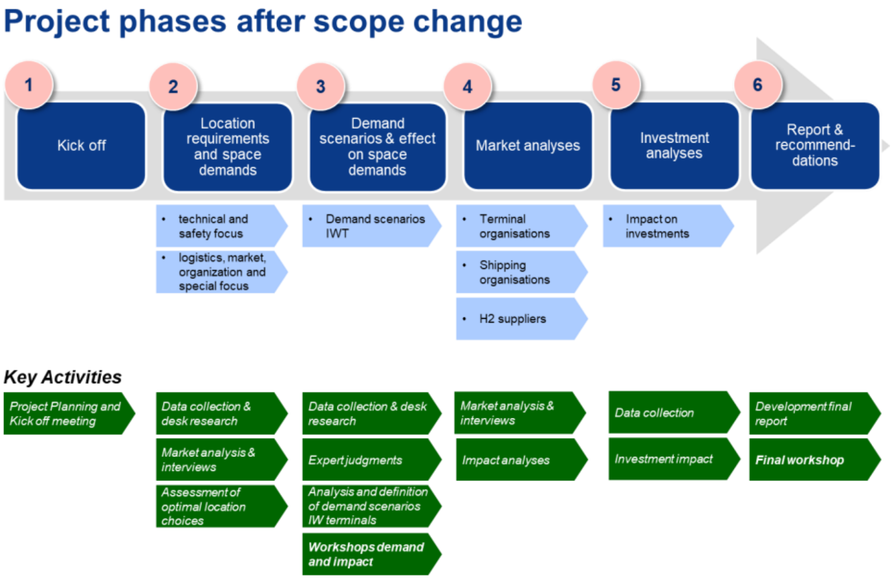
After this preface, chapter 2 describes the used project approach and methodology. Chapter 3 addresses the assumptions used for the analyses and the study. As mentioned, no analysis was made of various bunker scenarios, but rather of the impact of using H_2-containers in inland navigation. Chapter 4 therefore deals with these effects. The H_2-containers must be loaded and unloaded from inland vessels. The location requirements and spatial demands of this are analysed in chapter 5. Based on the demand study (sub-study 1.1c) an analysis has been made of the demand for hydrogen as a fuel for inland navigation in the three different port areas. This includes also possible spatial demand changes and safety demands (chapter 6). On the long term, the use of other forms of hydrogen carriers will become possible, which will also allow vessels to bunker via a hose. Chapter 7 describes qualitatively the impact that the use of these new forms of hydrogen carriers could have on the use of H_2-containers, on the logistics and investments of the parties involved (chapter 8). Chapter 9 finalizes this report with the conclusions and recommendations.

3 See annex for an overview of interviewed parties.

Chapter 2 Project approach and methodology

The project approach and methodology used is shown in figure 2.1.

Figure 2.1 Project approach and phases RH2INE location study



1 During the ***kick-off meeting*** (phase 1), the project objective and approach were agreed upon. Also the preliminary results of the other sub-studies were discussed. This included the results of the study 1.1 b "Hydrogen bunkering scenarios" and the sub-study 2 "design study". As described in chapter 1, based on these results it was agreed that the scope of this location study was adjusted to focus only on swapping H_2-containers (compressed H_2 gas, 300 and 500 bar pressure). It was also clear at that stage that the final reports of the sub-studies had a delay. Because of that, also this Location study was forced to adjust its timetable accordingly. Based on the adjusted scope, the next project phases were agreed upon with the RH2INE consortium.

2 ***Location requirements and spatial demands / bunker variants:*** It was not necessary any more to define location requirements and spatial demands for different bunker variants, but only for container swapping at the different ports. Based on other sub-studies, desk research[4] and the existing expertise of the three consortium partners (Buck Consultants International, CE Delft and Kiwa technology), the location requirements and spatial demands were defined generically. This was done for the focus areas: "technical and safety focus areas" (e.g. technical requirements for storage and distribution, needed infrastructure, environmental requirements, regulatory aspects, etc) and the logistics, market, organization and other focus areas. Based on the two parallel analyses, a total

4 See the bibliography.

overview was made of all location-based requirements and expected spatial demands. For each port, it was examined separately whether there were additional or different location requirements or spatial demands. In interviews with stakeholders, it was assessed whether more requirements were relevant or whether the overviews were complete. During a workshop the requirement indicators were assessed for different terminal types.

For this phase an extra analysis was made of the safety requirements for swapping hydrogen containers and how they affect the location. This has been based on the information of Study 1A Sub-activity 1.1d and ADN and ADR.

3 ***Demand scenarios & effect on spatial demands*:** The objective of this phase was a detailed survey on hydrogen demand requirements for each port and their effect on spatial demand and infrastructure requirements (for all modes of transport). This phase consists of three steps. Defining the demand scenarios (1), determining the effects of these scenarios on the spatial demands and infrastructure requirements (2) and a workshop about the provisional results (3).

I. Definition of demand scenarios for swapping containers for each port using Study A of sub-study 1a and Study B of sub-study 1a as a starting point. The key activities for this step were:
   - Desk research based on the estimated hydrogen demand development of the Study C of sub-study 1a and on other public reports on demand development, which includes among other scenarios on the development of hydrogen production and of hydrogen demand of the transport sector by 2030 and 2050.
   - Expert judgment on demand of hydrogen in local region of ports.
   - Analysis of the information found and definition of demand scenarios for each port for the short-term (this starts with the short-term deployment of one ship as a piloting ship and realization of the first bunkering locations in for example 2025) and long-term (rollout up to 100 ships, for example in 2035, growing demand). It is described how the growth path progresses from the short term to the long term.

II. Defining the effects on spatial demand and infrastructure requirements:
An impact analysis of the growth in demand included in the demand scenarios on spatial demand and infrastructure requirements in the short-term and long-term was executed, based on the requirement overviews. The growth in demand calls for a hydrogen bunker infrastructure that can be scaled up, which could require more space over time. The implications on the spatial and infrastructure requirements were worked out.

III. Workshop demand and impact: To gain support, a workshop was held about the demand scenarios and the effects of these scenarios. Based on the discussions, the most plausible scenario was defined.

4 ***Market analyses:*** In this phase, based on interviews, an analysis was conducted on how different market parties (barge organizations, terminals, H_2 suppliers) think about the concept of swapping containers. Expected challenges and problems with the hydrogen distribution resulting from the demand for H_2-containers for inland shipping were identified. For example, during the interviews with H_2 suppliers the transport of hydrogen, the functioning of filling stations and the supply of hydrogen were important aspects. No substantial desk research was executed for this phase. Also no modelling/detailed calculations were made. Finally, for each port, it was examined whether there are additional aspects needed to be included in the analysis or whether aspects should be omitted.

5 ***Investment analyses:*** The design study has already outlined a rough business case and rough estimation of the costs of swapping containers. This phase examines the impact of the growth scenarios for the three ports on any required investments. Qualitative descriptions are also given about the effects of a possible switch from swapping containers to other ways of bunkering in the long term. Finally a view has been given of possible ownership scenarios for the H_2 containers.

6 ***Report and recommendations:*** all results have been summarized in this report and recommendations have been defined based on these results.

Chapter 3 Assumptions used

Before the analyses, calculations and elaborations were started, assumptions were made about a number of aspects an elements that are relevant for this report. These assumptions affect various parts of this study and are therefore listed here. These assumptions are partly conclusions from previous sub-studies and partly based on expert opinions which were agreed upon during workshops with the RH2INE consortium.

3.1 Scope

It was already stated earlier, the scope of this location study is limited to:

- For the short and midterm to swapping tube containers with pressurized hydrogen at container terminals. Chapter 5 substantiates why container terminals are the best option for swapping containers.
- Most container terminals are used to, and capable, to handle dangerous goods containers. Because these container terminal organizations are experienced in handling containers with dangerous goods, they have trained personnel, implemented safety procedures and regulations and have special storage areas available, these terminals can also handle H_2-containers.
- On the long term other forms of hydrogen like liquid fuels (e.g. LOHC, ammonia or sodium borohydride) are expected to develop. Because bunkering via a hose is faster and the operational costs will be lower than swapping containers, a transition can be expected with the introduction of bunkering via hose. At this moment, it is however too early to indicate a preferred technique and type of hydrogen which will be used on the longer term.
- Container terminal organizations have indicated that they don't have space available at their terminals to develop a filling station at the terminal terrain, so that empty H_2-containers can be filled directly at the terminal. H_2-containers will therefore be filled at other locations (probably dedicated filling stations).
- This study focusses on the H_2-bunkering locations for barges. The location choice of filling stations is out of scope.
- For the logistics of inland navigation and the swapping of H_2-containers as well as for the business case, it is important that H_2-containers are filled relatively quickly, so that they can be re-used on the short term (see chapter 4). For that reason, this study qualitatively examines the impact of handling H_2-containers for filling stations (financial, organizational, logistical, safety). This analysis is based on interviews.
- This study includes swappable containers filled with compressed H_2 to be used in inland navigation. In the short and medium term, it does not appear that other modes of transport will also use H_2-containers as a source of fuel. Studies have been conducted about the use of H_2-containers for rail transport, but this seems difficult to achieve from a logistical point of view[5].

[5] See Bibliography nr 8.

3.2 Hydrogen-demand

- The demand for hydrogen to be applied for inland shipping on the Rhine corridor is based on the RH2INE Demand study (sub –study 1.1c, DNV-GL):

Table 3.1 Demand scenarios RH2INE demand study

Year	Low (tons)	Medium (tons)	High (tons)
2030	5.000	18.000	48.000
2040	10.000	36.000	104.000

Vessels per day	Low (tons)		Medium (tons)		High (tons)	
Fuel consumption H_2 per round trip (tons)	1,8	2,8	1,8	2,8	1,8	2,8
2030	11	7	38	25	103	66
2040	21	14	77	49	222	143

The following assumptions were made for these demand scenarios:
- Number of vessels per day based on 52 weeks, 5 days per week.
- Total demand includes all vessels that (partly) sail the Rhine route and also includes for example Rotterdam – Amsterdam and Rotterdam – Antwerp traffic.
- All calculations are based on the reference ship (containership, 135 m long, 421 TEU (source: pre-study ZBT and Energy Engineers, 2021)) with a consumption of 1,8 to 2,8 ton of H_2 per round-trip (appr. 70% upstream, 30% downstream) on the Rotterdam – Duisburg journey.
- For allocation of demand to ports, BIVAS-data (2018) is used. This data was compared with the source files on which the demand study was based (Prominent data). BIVAS data is more detailed and therefore more useful for this analysis, but the volumes and flows are quite similar. It was therefore decided that BIVAS data could be used for this study (more in chapter 6).

Chapter 4 Effect of swapping hydrogen containers on logistics of inland shipping

4.1 Introduction

This chapter describes the effects of swappable hydrogen containers on logistics compared to diesel fuel, mainly based on the interview outcomes. These include effects on operations, planning, training, but also how containers must be supplied and filled and the effect on filling stations (incl. transport between terminals and filling stations). The Design study has already described some effects.

The structure of this section follows the hydrogen supply chain 'upstream': from inland vessels to container terminals[6], to hydrogen container transport, to filling stations. Hydrogen production itself is out of scope and will therefore not be treated separately.

4.2 Inland vessels

4.2.1 Characteristics of containers

For inland vessels that switch to a swappable compressed hydrogen container system, it would make sense to make use of 20-foot (20ft) or 40-foot (40ft) containers, because these are standard container sizes (falling under ISO norms), which can be easily transported by existing tube trailer trucks. If a filling station operator or a separate company sets up a container system and rents out the containers when used by inland vessels, these containers will probably be 20ft or 40ft containers. Which container size is preferable for a ship operator depends on its needs. 20ft containers are more flexible and take up less cargo space, but 40ft containers provide a higher transport range. The first designs of swappable hydrogen containers are 40ft containers.

Another choice is between Type 2 or Type 4 cylinder. Type 4 cylinder are made from composite materials, are lighter and are able to handle higher pressures. On the other hand Type 2 are made with a metal inner layer which is affected less by diffusion and is better able to resist against heat. A requirement is that the weight of the containers does not surpass the weight allowed to be transported by road vehicles.

[6] In chapter 5 the choice of container terminals as swapping locations is substantiated. It also describes the location criteria in more detail.

Standardized containers are an important enabler for a swappable container system, which is why 20ft and 40ft containers is preferred form a logical choice. However, an interviewed hydrogen producer thinks that hydrogen containers will initially be designed for specific vessels, so that the containers can be placed on the vessel with minimal impact on cargo space and minimal safety risks. This may be true, but tailor-made containers will be more costly to produce. Also, they may need to be certified separately in order to comply with safety regulations.

The containers should have safety measures which reduce the risks during incidents:

First, to keep hydrogen in the tanks under abnormal circumstances, the containers have features such as solenoid valves, pressure regulators and pressure sensors.
Second, to prevent the tanks from exploding, an overpressure protection (Thermally-activated Pressure Relief Device: TPRD) has also been installed to prevent the internal pressure from rising too much in the event of extreme external heating.

Another measure to vent hydrogen is the Pressure Relief Valve (PRV). The PRV is installed on the regulator between the tank and the fuel cell stack and will operate when the pressure in the low-pressure lines between the regulator and fuel cell stack rises too much.

There are also two main pressure levels to be considered for the hydrogen gas pressure in the containers: 300,500 bar.[7] Although different pressure levels might be used in the swapping system in parallel, this would reduce the possibilities for sharing containers. It seems more likely that a single pressure level will be used in the end. Here too, the desired transport range of the vessel is an important decision criterion for ship operators. The range improves by 40 to 66% when moving from 300 bar tot 500 bar, as the hydrogen storage capacity increases from 312 kg (Type II cylinder) or 371 kg (Type IV cylinder) for 300 bar to 518 kg for 500 bar (ZBT and EE, 2021). However, 300-bar containers are a bit cheaper, and the costs of on-board safety requirements may be lower for ship operators in the case of 300-bar containers. Finally, the regulations of 500-bar containers still contain some gaps, unlike 300 bar containers. The inland shipping sector appears to prefer the 300-bar containers.

4.2.2 On-board configuration

The on-board configuration of the hydrogen containers has first and foremost an impact on transport range and available cargo space. In general, the more space on the vessel is used for the hydrogen containers (also depending on the used pressure), the higher the transport range (requiring fewer terminal visits for hydrogen container swapping), but the lower the vessels cargo space for bulk goods or containers. The number of hydrogen containers and the container size have an obvious impact on the required space on the vessel. Interviewed ship operators prefer sailing with 2 or 3 containers and accept that this leads to more frequent terminal visits. The 'stackability' of the containers on the vessel also has an impact: If the containers are allowed be stacked, less surface area on the vessel is needed. Furthermore, the location of the containers on the vessel has an impact on the safety distances that must

[7] 700 bar is an option as well, but from the interviews, it emerged that the expectation is that in the short and medium term the 700-bar containers will not be used. We therefor focus on 300 and 500 bar.

be maintained, for the safety of the crew. It might also be the case that the hydrogen containers, for safety reasons, should be placed in a specific section of the vessel.[8] Compared to diesel vessels, the remaining cargo space will probably be less, but the extent of the space reduction depends on all of the above.

The hydrogen containers are probably connected to the fuel cell system by means of multi-connectors (which communicate with the safety devices on the vessel), pressurized air and automatic valves. The crew must take care that the containers are properly connected and disconnected, before and after the swapping of the containers, for which they need to be trained (see paragraph 4.2.4). Another possibility is to use a manifold system which could connect multiple containers while being moored and prevent the need to switch connections manually while sailing. Installing additional safety devices like H_2 detection equipment and a ventilation system would warn the crew during incidents and prevent dangerous situations.

4.2.3 Logistic planning

Compared to inland vessels running on diesel, inland vessels using hydrogen containers must ‘refuel’ more often. In addition, the number of terminals where these vessels can 'refuel' will be more limited than for diesel-powered ships, because the limited hydrogen demand and the need for additional storage space makes a limited amount of hydrogen swapping terminals cost-optimal. These are two main differences that make the logistic planning of ship operators more challenging.

The swapping of two hydrogen containers on a vessel only takes about 5 minutes, but including the arrival at and departure from the terminal it takes 30 minutes. Depending on the layout and available space at individual container terminals, hydrogen container swapping could be performed simultaneously or right before or after the transhipment of goods containers, in which case 2 to 4 additional containers need to be moved. This may take some additional time at the quay compared to diesel vessels and compared to if the hydrogen container swapping can be done simultaneously with the (un)loading of goods containers. This extra time however, can often be accommodated in the total transport time of a vessel.
In case the hydrogen containers are stored at another quay (or terminal), the vessel might need to sail to that quay to swap hydrogen containers, which would take a lot more time. However, the containers could also be transported by truck to the vessel’s location. Additional terminal visits for container swapping, without any (un)loading of goods containers, will take up the most additional time (in the order of 30 minutes per visit), compared to diesel vessels. The lower the transport range of the hydrogen-powered ship, the more ‘refuelling time’ is needed. In the case of bulk vessels, visiting a container terminal would take up too much quay capacity (a minimum ‘call’ of 10-20 containers per ship applies at such terminals), so they would need to visit specific inland terminals for hydrogen container swapping.

[8] On the one hand, placing hydrogen containers in the front of the ship increases the distance to the crew space, and could therefor improve crew safety. On the other hand, placing the containers at the back of the ship (close to the engine space) reduces the length of connecting tubes and reduces the impact of collisions. Which factors weigh more strongly may depend on specific ship conditions, such as ship size and the number of crew members.

The logistic planning by ship operators will be easier if the transport range increases, but as mentioned this goes at the expense of cargo space. It will not be economically optimal to minimize the amount of terminal visits only for hydrogen system swapping. Furthermore, it takes some extra time to (un)load the hydrogen containers in addition to the goods terminals. It can be concluded that compared to operating on diesel, ship operators have to schedule (some) additional (un)loading time and sometimes additional terminal visits (which increases the total ‘refuelling time’ the most), complicate the task of logistic planning. These terminal visits need to be fit into the overall time schedule of transporting goods through the Rhine corridor.

To reduce the risks of delays, it is important that the ship operators can rely on the availability of filled hydrogen containers at the terminal, available quay and crane capacity, a limited waiting line of other hydrogen-powered vessels that need to swap containers, and a free arrival and departure route at the terminal. Terminal operators have an influence on all of these, but the availability of full H_2-containers, which is obviously most critical, is first and foremost the responsibility of either the hydrogen container supply company or the ship operator itself.

If the ship operator has signed a supply contract with a specific hydrogen container supply company (with the ship operator renting the containers), that company is responsible for the availability of full hydrogen containers, and also for the hydrogen quality. A high hydrogen quality is important, because impurities in the hydrogen damage the fuel cell system. However, the risk will probably be shared partly with the ship operator, i.e., the lost income will not be completely reimbursed by the supply company.

An alternative organizational scheme would be for the ship operator to buy containers itself and make sure itself that the containers are filled and available at the right place at the right time. But then he would bear the investment costs of the hydrogen containers, including the ones that are filled while the ship is sailing, and the full risk of unavailability if something goes wrong. Also, he would be responsible for the certification and maintenance of the hydrogen containers. This scheme would introduce new logistical challenges to the ship operator. All in all, it appears more likely that a dedicated hydrogen transport company (which could be the filling station operator, see below) will take up the task of supplying full hydrogen containers. Such a company can do this on a larger scale, for multiple ship operators, thereby reducing costs and risks of unavailability.

4.2.4 Preparation / operational impact

To prepare for sailing on hydrogen using swappable hydrogen containers, a ship operator needs to replace the diesel engine and diesel tanks on its ship with a fuel cell system and a connection system for hydrogen containers. These systems must be certified. Also, using hydrogen as a fuel for inland shipping should be allowed by the national regulatory frameworks. Currently, hydrogen is not covered in ADN (European agreement for transport of dangerous substances through inland waterways).

The ship operator should also make sure that sailing on the hydrogen-powered vessel and any manual task related to the on-board hydrogen system do not pose a threat to the crew. The general safety regulations, and any specific safety regulations for hydrogen systems on inland vessels, should be met.

Furthermore, the vessel's crew must be trained to handle the hydrogen system and containers. All personnel on board should get a basic training. If switching of hoses to (de)couple the hydrogen containers on board with the fuel cell system is done by the crew (systems with automatic switching exist as well) this is even more important. The crew should be taught the safety and emergency procedures: What distances must be kept, what to do in case of a fire, etc. If the goods that are transported by the vessel influence the safety risks and the applicable safety regulations, the crew should learn this as well.

4.3 Container terminals

4.3.1 Location of terminals

In a swappable hydrogen container system for inland shipping, we can distinguish several potential types of 'swapping terminals': ***deep sea container terminals**, **container terminals in the port** and **inland container terminals***. The deep sea container terminals are the largest, existing terminals for goods containers in the ports. Due to their tight schedules, focus on the larger seagoing ships, scale and automatized processes, deep sea container terminals are not likely to be interested in hydrogen container swapping. The other container terminals and inland container terminals are smaller terminals on the Rhine corridor (not necessarily in a port) and are in a better position to meet the demands from ship operators with hydrogen containers onboard. Inland dry bulk terminals are not likely to become hydrogen swapping locations as result of the high investments in cranes and extra quay space.

Inland container terminals

The locations of the container terminals are already known, but within the terminals there may be multiple potential sites for transhipment and storage of hydrogen containers. From the perspective of the terminal operator, it would be logistically beneficial if the site is well accessible for tube trailer trucks, and if the site is nearby the quay of the hydrogen-powered ships. This would help to minimize the impact of the movement of hydrogen containers for overall logistics in the terminal.

The locations of the inland container terminals have yet to be determined[9]. What number of inland container terminals and which exact locations are economically optimal, considering both the business cases of terminal operators and ship operators, depends among others on

9 Location selection criteria are described in more detail in chapter 5.

the sailing routes of the vessels, number of vessels using hydrogen, available or potential terminal storage and transhipment capacity, proximity to the sailing routes, and proximity to the hydrogen filling station. From a high-level economic perspective, it would be beneficial if the number and locations of inland terminals could be determined on a system level, by means of an economic model in which all important financial variables are considered.

4.3.2 Logistic planning

Container terminals

Containers filled with hydrogen are considered dangerous and therefore need to be placed separately from general goods containers. Also, environmental requirements only allow for temporary storage. In case of longer storage times additional measures might need to be taken. As a result, the handling of hydrogen containers will create additional logistical efforts for the container terminal operator, compared to additional goods containers.

In case hydrogen-powered vessels swap hydrogen containers at the same dock, right before or after the (un)loading of goods containers, the hydrogen containers need to be moved from the separate storage area to the ship. If the cranes at the dock cannot reach the separate area with hydrogen containers, this will add to the number of container movements in the container terminal. However, the impact on handling time per ship will be quite small in this case (swapping two containers takes approximately five minutes). The fact that hydrogen containers are allowed to be stacked in the terminal makes it more likely that the containers can be stored close to the location of (un)loading of goods containers.

In case the hydrogen-powered ships would be required to sail to another quay for the purpose of hydrogen container swapping, the number of hydrogen container movements in the port area may reduce (if the hydrogen containers are stored outside of reach of the cranes), but the movements of ships in the port waterways would increase, which may affect traffic of ships and thereby lead to delays in the (un)loading schedules. Also, if the number of swapped hydrogen containers per day is low, the scheduling of cranes and personnel becomes less efficient in this case.

Both for the container terminal operator and the ship operators, it would be most time- and cost-efficient if the transhipment of goods containers and hydrogen containers could be done at the same location and during the same call. An important precondition is that sufficient full hydrogen containers are available in the container terminal.

At less busy inland container terminals there is often enough quay capacity to handle hydrogen containers directly, as fewer ships visit the terminals and the transhipment schedules are less tight. This makes the introduction of a hydrogen swapping system into the overall terminal logistic schedule less challenging for those terminal operators.

4.3.3 Preparation / operational impact

The terminal operator should have a permit for handling swappable hydrogen containers, at the required volumes and handling capacity. This might already be covered by permit that the terminal operator already has (such as a permit for handling dangerous substances and gasses), but the operator should make sure that this is the case.

Furthermore, the terminal operator should make sure that the swappable hydrogen containers can be moved, stored and swapped safely, and that these operations take place in accordance with the safety regulations. Containers with dangerous substances must be transported/stored according to the rules of the ADR[10]. More information can be found in paragraph 5.2.

4.3.4 Safety Demands

The terminal operator does not require new handling equipment for the swappable hydrogen container system; in general the cranes and container trailers that are used for the dangerous goods containers can also be used for the hydrogen containers. However, the container terminal personnel should be trained to handle the hydrogen containers according to the safety requirements, and to inspect the hydrogen containers that arrive at the terminal.

4.4 Hydrogen container transport

The swappable hydrogen containers will be filled at a hydrogen filling station (see below) and then transported by truck to the (container or inland) terminal. With a trailer truck, two 20ft containers or one 40ft container can be transported. On the way back, the truck can transport empty hydrogen containers from the terminal to the filling station.

4.4.1 Organizational model

A main question for the development of a swappable hydrogen container system is what the organizational model will look like, i.e., how the different roles and responsibilities are distributed among market parties (filling station operator, terminal operator, ship operator, transport company, third parties). This question manifests itself most of all when considering the activity of hydrogen container transport. Important underlying questions are:

- Which party owns the hydrogen containers?
- Which party transports the hydrogen containers?
- Who is responsible for the availability of full hydrogen containers at the right place at the right time, with the right hydrogen quality?

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[10] *See https://rvs.rivm.nl/gevaarsindeling/ADR.* The applicable regulations change at the moment that the hydrogen container is connected to the fuel cell system and becomes part of the ship.

The market party who invests in the compressed hydrogen containers owns the containers and is responsible for their proper functioning and safety of use. This means that the owner must take care of certification and maintenance of the containers. Because the hydrogen containers are costly (see Chapter 8), and it is inefficient to acquire and use specific containers for specific ship operators, a container pooling system is probably most viable. Different parties involved in the hydrogen container swapping system could set up a joint venture, with shared ownership of a pool of hydrogen containers or a large (international) company can take up this role. The parties in the joint venture would share the purchase and maintenance costs of the containers and could subcontract a market party to take care of the logistics of transporting containers between the refilling station(s) and the swapping terminal(s)[11].

The market party that transports the hydrogen containers could be a dedicated road hauler (transport company), but it could also be the refilling station operator. Although filling station operators may be hesitant to take up this role, the filling operator is already responsible for providing hydrogen of high quality. It is important to note here that, in order to prevent conflicts on accountability of providing low-quality hydrogen, containers should only be refilled by a single filling station operator, as put forward by ZBT and EE in their final report of the RH2INE Design Study (ZBT and EE, 2021). Having said that, it should be possible to give the responsibility on availability (i.e., making full containers available at the right place and time) to a dedicated transport company. The refilling station operator would then be responsible for the hydrogen quality, and the dedicated transport company for the availability of full hydrogen containers.

4.4.2 Logistics planning

Making sure that full hydrogen containers are present in the right terminals at the right quantities and at the right time will be a complicated logistical puzzle for the hydrogen transport/logistic company. This company is faced with all kinds of constraints: the limited storage space and storage duration in terminals, the limited total amount of containers, the storage capacity and refilling capacity at refilling stations, distances between filling stations and terminals. In addition, the demand for full hydrogen containers will to some extent be unpredictable, even when the overall logistic routes of hydrogen-powered vessels are known and ship operators communicate their needs in advance. And there may also be unforeseen traffic jams on the road and required maintenance to the hydrogen containers. Here, a larger pooling system, in which multiple filling stations and terminals cooperate, would help to create flexibility and the ability to meet the demand more efficiently, and thus more cost-effectively.

If filling stations are close to the terminals, it would make the logistical puzzle easier: It increases the possibilities for short-term rescheduling of filling and transporting swappable hydrogen containers, thus improving the security of supply for the ship operators. A second factor that might reduce the logistical challenge is the availability of a separate storage location for hydrogen containers, at a strategic location between the refilling station(s) and the terminal(s). This would introduce additional operating expenses and the need for permits for the new storage location, but could lower the storage needs at the refilling stations and

[11] The same organizational question applies to the use of battery containers. For the elaboration of these types of organizational issues, the parties involved may be able to learn from each other and/or strengthen each other.

terminals. Furthermore, if the transport company can take into account the routes of hydrogen-powered ships on the Rhine corridor and the operating range of these ships, the supply of full hydrogen containers can be planned more efficiently, while also reducing the risks of unavailability. For this purpose, it would be helpful if the ship operators would communicate their demand for full containers (locations and times) to the hydrogen container supplier.

Planning for both 20ft and 40ft containers would be more complex, but the additional challenge compared to the (already complex) planning for a single container size swapping system may be limited. However, for ships that are sailing with tailor-made containers, a pooling system does not work. Such containers would need to be refilled and redelivered to the same ship operators. From the perspective of hydrogen container refilling and transportation, this would be inefficient and expensive.

4.5 Filling stations

The filling stations for refilling the swappable compressed hydrogen containers will probably be located close to a hydrogen production facility or close to the national hydrogen network which is under development. These filling stations may also function as station to refuel hydrogen tube trailers and high duty vehicles. Existing filling stations for hydrogen tube trailers (for supplying refuelling stations) could also be used for filling hydrogen containers, if the capacity of the station allows for this. If such 'multi-purpose' filling stations are used or developed, their location will not only be based on the distance to the port / container terminal, but also on distance to other supply points and accessibility for road vehicles.

Currently there are tube trailer filling stations in Rotterdam and in the Ruhr area at the production sites of a (grey) hydrogen producer. Furthermore, a maritime organisation has opened the first multimodal hydrogen refuelling station in the world, in Antwerp in 2021. The hydrogen is produced locally with an electrolyser. This station can refuel ships, cars, trucks and buses, and surplus hydrogen is pumped into tube trailers, to supply hydrogen to other locations.[12] Moreover, there are other development plans for electrolysers that include a filling point for tube trailers, such as in the HyStock project in the Province of Groningen.[13] A complete overview of current tube trailer filling station locations is not available, but we highlight that some tube trailer filling stations are already present in the Rhine corridor, and that these can also be used for filling hydrogen containers.

If a new filling station is built mainly or solely for the purpose of filling hydrogen containers for inland shipping, the design of the filling station could be optimized for this. Parameters than could be optimized include the dimensions of the buffers, the capacity of the compressor, filling speed, handling capacity (personnel) and storage space. A hydrogen container can be filled in 3 to 4 hours. The filling speed improves with a higher compressor capacity, but that would increase the need for pre-cooling of the hydrogen. More information on this can be found in the Design Study (ZBT and EE, 2021).

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12 https://allesoverwaterstof.nl/opening-eerste-multifunctioneel-waterstoftankstation-ter-wereld-in-antwerpen/
13 https://here-comes-the-sun.nl/projecten/hystock

As mentioned above under the description of hydrogen container transport, the filling station operator is responsible for providing high-quality hydrogen, as the on-board fuel cell systems require pure hydrogen. The filling station operator could also take up the role of hydrogen container transport, but a more viable market arrangement appears to be a container pooling system, in which a dedicated company is responsible for transporting the hydrogen containers between the refilling stations and terminals.

4.6 Findings on logistic effects

Overview of effects of a swappable hydrogen container system on logistics, and findings

Factor	Effects and findings
Container size and design	• For the ship operators, a tailor-made design would be most applicable in operational terms, but then the containers cannot be used by others. • A 40 ft-container is less flexible than a 20ft container, but provides a higher range. Preferences of ship operators for either or both depend on specific ship conditions and travel needs. • A system based on standardized 20ft and/or 40ft containers improves efficient utilization of containers.
Hydrogen pressure	• Two main pressure levels for hydrogen containers are 300 bar and 500 bar. To increase the potential for container sharing, the selection of a single pressure for the swapping system is desirable. • A 300 bar container system appears preferable, among others because of the lower container purchase and filling costs compared to 500 bar containers.
On-board configuration	• There is a trade-off between transport range and cargo space. • Ship operators prefer sailing with 2 or 3 containers and accept more frequent terminal visits for container swapping. • It is not yet clear if hydrogen containers can be stacked on-board. • It is not yet clear where the hydrogen containers should be placed on the ship (at front or back) in order to maximize safety. • With a manifold system, multiple containers could be connected to the fuel cell system without the need for manual switching.
Location of swapping terminals	• Hydrogen container swapping should at least be introduced at container terminals, where it can be integrated into the existing handling system of goods containers. • Suitable locations for inland container terminals depend on the routes of hydrogen-powered vessels, mooring capacity, proximity to the main sailing routes, and proximity to a refilling station.
Terminal visits	• Hydrogen-powered vessels must visit terminals more often for 'refuelling', compared to diesel-powered ships. • At container terminals, hydrogen swapping can probably be done during or before/after the (un)loading of goods containers. If the handling capacity is insufficient for this, the ships need to sail to a separate quay or terminal.

Factor	Effects and findings
	• At smaller inland container terminals, the (un)loading schedule is less tight, making container swapping easier to schedule, with lower waiting time. • For bulk ships, visiting a container terminal would take up quay capacity normally used for container ships.
Logistic planning	• Ship operators must fit additional terminal visits and/or additional handling time into their travel schedule. • Terminal operators need to fit the storage, transport and transhipment of hydrogen containers into the logistic schedule of goods container handling. • Existing filling station operators must allocate capacity and time to the filling of hydrogen containers. • For a hydrogen transport company, logistic planning will be most challenging. Obtaining information from ship operators on expected needs (hydrogen volumes, locations and dates) would be valuable.
Organizational model	• A container pooling system (operated by a joint venture of filling station operators, terminal operators and other stakeholders or a large (international) specialized company) would result in shared investment costs and efficient routing and utilization of hydrogen containers. • A dedicated transport company can be subcontracted. This company will then be responsible for making full hydrogen containers available at the right place and time. • The filling station operator is responsible for delivering hydrogen at high quality. • Ship operators rent the hydrogen containers they use, which could be factored into the hydrogen price or be charged separately.
Preparation / operational impact	• Ship operators need to replace their current propulsion system with a fuel cell system and a connection system for hydrogen containers, train personnel, and take on-board safety measures. • Terminal operators need to obtain a permit for hydrogen container handling, prepare a separate terminal section for hydrogen container storage, and train personnel, but this is also valid for other dangerous goods. • Filling station operators should create capacity for filling compressed hydrogen containers. When new filling stations are built, the location and design could be adapted to match the needs of inland shipping. • A joint venture of hydrogen parties (or another investor) should purchase hydrogen containers, certify the containers and subcontract a transport company and a maintenance company. • A dedicate hydrogen container company should get permission to transport hydrogen containers by road and determine if a separate storage site for hydrogen containers is profitable.

Chapter 5 Location requirements and spatial demands

This chapter discusses the various requirements for a location where hydrogen containers can be swapped. These requirements are compared for different types of terminals. Paragraph 5.2 also gives a more detailed explanation of the various safety requirements that must be considered.

5.1 Analysis and assessment of location requirements and spatial demands

With the help of the BCI location choice methodology and desk research (RH2INE sub-studies, ADR, ADN, etc)[14], existing expertise and interviews, the location requirements and spatial demands for swapping H_2-containers were defined on technical, safety, logistic, market and organization focus areas. The defined requirements with their explanation are shown in the tables on page 24-30.

During a workshop with the RH2INE kick start study consortium, these indicators were agreed. It was also agreed that these indicators would be compared for three types of terminals. In the short and medium term, it is expected that H_2-containers will mainly be used as fuel carrier by container vessels and dry bulk vessels. These vessels have the space to place containers for this purpose. Other types of vessels will have to undergo major modifications before that is possible. In the short and medium term, this is therefore not expected to happen. Because the focus is on these two types of vessels, it is also in line with expectations - and this was also endorsed during the interviews - that the containers can be transhipped at the terminals where these ships naturally go. These are the container terminals and dry bulk terminals. In addition, there is always the possibility, when the market demand is high enough it, to develop a green field location for the transhipment of H_2-containers. The location requirements and spatial demands are therefore compared for swapping of H_2-containers at three types of locations:

- Existing container terminals
- Existing (dry) bulk terminals
- Green field locations

For each port, it was examined separately whether there were additional or different location requirements or spatial demands, but there were no specific reasons to assess the indicators differently for the different ports.

[14] See also the bibliography.

In the previous sub-studies, it has already been indicated that the pressure affects the amount of energy that can be used per container. For the same transport, more H_2-containers are needed at 300 bar than when the containers are filled at 500 bar. Transferring these containers is done in the same way, but because more containers are required, this also affects the use of space and transfer capacity. For that reason, for each type of terminal, two different types of H_2-containers were examined, namely at 300 bar and 500 bar.

Using the traffic light method, the different types of ports were compared for each sub-indicator. For each sub-indicator it was determined for which type of terminal and for which type of gas pressure the sub-indicator fits best (dark green), fits reasonably well (light green), moderate fit (orange) or fits poorly (red). This valuation was first completed by experts. Subsequently, the ratings were tested during a workshop with the RH2INE consortium. The ratings for each sub-indicator are shown below.

[dark green]	Good match
[light green]	Reasonable match
[orange]	Moderate match
[red]	No match
[yellow]	Not relevant

Priority indicator

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
Footprint	Surface in m2	Dedicated space needed for handling and storage of H_2-containers. Existing container terminals do not need extra space, because H_2-containers are handled as regular dangerous goods containers and will be part of the regular business. Dry bulk terminals or green field locations are not yet handling containers and therefore need specific space.	not relevant on short & mid term		extra space required for container crane, stack, storage		space required for quay, container crane, stack, storage	
	Price of land	When extra space is needed, the price of land is an important factor for the financial feasibility.	not relevant on short & mid term		extra space required for container crane, stack, storage		space required for quay, container crane, stack, storage	
	Availability plots/land	When extra space is needed (on short term or for growth on longer term), availability of land is of course very important for the needed extension of the terminal.	not relevant on short & mid term		expansion needed for extra space required for container crane, stack, storage		space required for quay, container crane, stack, storage	
	Storage capacity	Sometimes specific storage capacity is needed (H_2-containers must be stored at specific dangerous goods areas). Storage is regularly allowed for maximum 24 hours. The hydrogen storage capacity of 500 bar containers is higher than the 300 bar container. With the same fuel demand, fewer 500 bar containers are needed than 300 bar containers and therefore less storage capacity.	special storage capacity needed for dangerous/hazardous goods 20ft, 30ft, 40ft containers	special storage capacity needed for dangerous/hazardous goods 20ft, 30ft, 40ft containers	special storage capacity needed for dangerous/hazardous goods 20ft, 30ft, 40ft containers		special storage capacity needed for dangerous/hazardous goods 20ft, 30ft, 40ft containers	
Existing H_2 Infrastructure	H2 infrastructure towards bunkering facility	Based on interviews, the assumption is that H_2-containers will not be filled at the terminals themselves, but at a filling point at a different location. The infrastructure (road, water, rail) must be suitable (particularly with regard to regulations) so that	transport of dangerous/hazardous goods must be possible on road		transport of dangerous/hazardous goods must be possible on road		transport of dangerous/hazardous goods must be possible on road	

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
		H_2-containers are allowed and can be transported to and from the terminal.						
	Location of H_2 refilling	The further the container filling station is from the terminal, the higher the transport costs to/from the terminal. These costs are important for the total business case. Also the quality of the infrastructure and lay-out of the infrastructure is important (less chance for incidents, efficiency).	shortest possible distance to the container filling station		shortest possible distance to the container filling station		shortest possible distance to the container filling station	
Location	**Waterfront location**	For the use of H_2-containers for inland shipping, it is essential that the containers can be transferred from land to water. The transhipment location must therefore be a waterfront location.	essential		essential		essential	
	Location in relation to H_2 supplier	The further away the container filling station is from the terminal, the higher the transport costs to/from the terminal. These costs are important for the total business case	shortest possible distance to the container filling station		shortest possible distance to the container filling station		shortest possible distance to the container filling station	
	Location in relation to highways	The closer the location is to the highway, the faster the delivery and removal of containers via road transport.	transport of dangerous/hazardous goods must be possible on road		transport of dangerous/hazardous goods must be possible on road		transport of dangerous/hazardous goods must be possible on road	
	Location in relation to local users	If local companies also use H_2 for their (transport)equipment, it can be an advantage if the terminal is nearby. In the short and medium term, it is not yet anticipated that these users will also use H_2-containers.	possible other local H_2 users are e.g. trucks, buses, terminal equipment. Container terminals are often located in industrial areas where these potential users partly operate nearby.		possible other local H_2 users are e.g. trucks, buses, terminal equipment. Bulk terminals are often located a bit further away from these activities.		the choice of a green field location can take into account other possible local users	

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
	Location in relation to potential truck users	Trucks are increasingly using H_2. In the future it may be efficient if the location of storage of H_2-containers is close to where many trucks pass. No benefit is expected in the short and medium term.	not relevant on short & mid term		not relevant on short & mid term		not relevant on short & mid term	
	Location in relation to other modalities	Other modalities can also start using hydrogen, for which it would be beneficial if the storage of the H_2-containers was near. Other modalities may also be important for the pre- and post-transport of H_2-containers.	not relevant on short & mid term		not relevant on short & mid term		not relevant on short & mid term	
	Location in relation to residential areas	Containers filled with H_2 are dangerous goods. The terminals must therefore take permits and procedures into account, so that the surrounding environment and residents are sufficiently protected. The greater the distance from habitation, the better.	handling of dangerous/hazardous should be possible and terminal must have the necessary permits		handling of dangerous/hazardous should be possible and terminal must have the necessary permits		handling of dangerous/hazardous should be possible and terminal must have the necessary permits	
	Impact on logistics	Transhipment of H_2-containers for inland shipping impacts the operational processes of inland shipping. That is why transhipment (loading and unloading) must be done as efficiently as possible. In the case of container ships, for example, this can take place directly during the "normal" loading and unloading process, so that no extra transhipment time is required. For inland vessels that have to make an extra stop for swapping the H_2-containers, the loading and unloading process must take place as quickly as possible when the ship is ready (minimum waiting times). Terminal organisations should therefore be flexible and/or strict planning is needed.	fast & flexible service needed		fast & flexible service needed		fast & flexible service needed	

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
	Location on Rhine	The location on the river has an impact on the risks associated with the transhipment of containers. Directly on the Rhine, the current is stronger and the waves and wind are often stronger than when the location is at an inlet or side canal.	on route of vessel, more swell of water, higher risk of collisions		on route of vessel, more swell of water, higher risk of collisions		on route of vessel, more swell of water, higher risk of collisions	
	Location on side canal of Rhine	As indicated above, a location on a side canal of the Rhine has fewer risks (calmer water). However, the distance is often longer (more away from the main route), and ships have to make more manoeuvres.	not on route of vessel, calmer water		not on route of vessel, calmer water		not on route of vessel, calmer water	
Infrastructure	**Quay length**	Sufficient quay length is necessary to be able to handle inland vessels. Preferably several ships at the same time.	available		probably not yet available for container vessels		to be developed	
	Crane (or reach stacker) availability	A crane or reach stacker is required to load and unload the H_2-containers to and from and on and off the ship. At container terminals they are already present, that is a pro.	available		not yet available		not yet available	
	Road infrastructure to the plot (accessibility)	Good connection to infrastructure (road, rail) is important for the supply and removal of containers.	available		available		not yet available	
	Accessibility by rail		can contribute to supply of containers		can contribute to supply of containers		can contribute to supply of containers	
	Digital infrastructure	A good IT infrastructure is important for a smooth operation.	available		not yet available		not yet available	
	Electrical infrastructure	For the production of H_2, it is important that a good electrical infrastructure with large capacity is nearby. It is less important for swapping containers.	not relevant on short & mid term		not relevant on short & mid term		not relevant on short & mid term	

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
		However, it is important for terminal operation that the electricity grid is sufficient.						
Safety	Standard Dangerous Goods (DG)	If dangerous goods are already stored and transhipped at a location, additional safety measures may not be necessary. This should be taken into account at other locations. It also depends on the location whether additional measures may be necessary.	no extra safety measurements required if terminal already handles dangerous goods (comply with ADR / ADN)		specific permits safety procedures required (comply with ADR / ADN)		specific permits safety procedures required (comply with ADR / ADN)	
	Extra safety requirements	If additional safety measures are required at a location, it has an impact on the suitability of a location.	no extra safety measurements required if terminal already handles dangerous goods		specific permits safety procedures required		specific permits safety procedures required	
	Safety zones and distances	Dedicated safety zones are required for the transhipment and storage of dangerous goods.	no extra safety zones required		Storage required for containers with dangerous goods		Storage required for containers with dangerous goods	
	Additional rules / procedures needed for transhipment	If additional rules or procedures are required at the location, it has impact on the suitability of a location.	handling possible with current procedures		new procedure required for containers		new procedure required for containers	
Organisation	Knowledge of handling dangerous goods	If an organization already handles dangerous goods, there is probably no need for additional training for H_2. If a location is not yet prepared, the personnel must be trained.	extra training for H_2 handling for terminal organisation often not necessary		training dangerous goods (incl. H_2) necessary		training dangerous goods (incl. H_2) necessary	
	Availability of permits	Permits are often required for the storage and transhipment of H_2.	most terminals will have required permits		specific permits safety procedures required		specific permits safety procedures required	

Indicators	Sub-indicators	Description of sub-indicator	Swapping container compressed H_2					
			existing container terminal		dry bulk terminal		green field	
			300 bar	500 bar	300 bar	500 bar	300 bar	500 bar
	Availability of qualified employees	For the storage and transhipment of H_2, qualified personnel is required who know how to handle H_2-containers.	extra training for H_2 handling for terminal organisation often not necessary		training dangerous goods (incl. H_2) necessary		training dangerous goods (incl. H_2) necessary	
	Knowledge of bunkering method	Degree of existing knowledge about transhipment techniques.	normal container handling		normal container handling		normal container handling	
Logistics process	Connection into current logistics processes	The extent to which the transhipment of H_2 containers is in line with the existing logistics process of the terminal.	loading/unloading during standard process		extra handling / stop needed		extra handling / stop needed, but can be at optimal location	
	Bunkering time	Total time of loading and unloading the H_2-containers for a ship.	loading/unloading during standard process		extra handling needed (extra terminal visit), but bunkering time can then be same		extra handling needed (extra terminal visit), but bunkering time can then be same	
	Impact of planning bunker location	The extent to which the transhipment of the H_2-containers has an impact on the existing operation.	loading/unloading H_2-containers must be done at specific moment and place on board		no impact		no impact	
	Necessary adjustment of inland vessel	Degree to which an inland vessel must be adapted to be loaded and unloaded.	no adjustment needed because of bunkering location		no adjustment needed because of bunkering location		no adjustment needed because of bunkering location	

During the interviews and workshop, it was indicated that the sub-indicators which are shown in red, are the most important requirements for a H_2-container swapping location.

5.2 Safety demands

Hydrogen is classified as a dangerous substance according to ADR and ADN. Its classification is 2.1.F. To prevent a dangerous situation safety has to be taken into account.

As hydrogen is a dangerous good safety requirements are necessary on site and licenses are needed. However many container terminals already are handling different dangerous goods including hydrogen. For these terminals the extra hydrogen containers will not have a substantial impact on their current procedures.

Some terminals might not be able to get the appropriate licenses due to the location or extra spatial requirements due to the extra safety requirements that are needed for dangerous goods. PGS15[15], a Dutch guideline based on ADR but not solely based on, gives specific instruction on the storage of container with dangerous goods.

The H_2-containers are temporary storage because the goods have a different destination than the terminal itself. Temporary storage is not defined by a certain time, however from the interviews with terminal operators, it appeared that often 24 hours is taken as a guideline. This means that there are exclusions from certain guidelines. For example, the Seveso directive 2012/18/EU[16] focuses on managing the risks and hazards of major accidents caused by hazardous substances. Article 2.2.C states that the following is excluded from the Seveso directive: "*the transport of dangerous substances and directly related intermediate temporary storage by road, rail, internal waterways, sea or air, outside the establishments covered by this Directive, including loading and unloading and transport to and from another means of transport at docks, wharves or marshalling yards;"* From this we conclude that this bunkering method is excluded from the Seveso directive. However, risks on site of a terminal still have to be managed appropriately. From an HAZID assessment performed by Future proof shipping there are dangers involved by hoisting a container into a vessel but they are not significantly different to other dangerous goods.

During normal operating conditions explosive condition do not occur. However, from ATEX guideline[17] it follows that is recommended to; prevent the creation of explosive atmospheres, avoid ignition of explosive atmospheres and limit the harmful effects of an explosion. For example; the accumulation of H_2 should be avoided.
During the interviews there has been some discussion if it is allowed to stack hydrogen containers. PGS15, a Dutch guideline based on ADR but not solely based on, states that it is allowed to stack containers of the same ADR class. This interpretation is not yet confirmed from German guidelines.

Environmental standards should also be taken into account. For example directive 2010/75/EU[18] on industrial emissions (integrated pollution prevention and control). This is

[15] See bibliography nr. 10
[16] See bibliography nr. 7
[17] See bibliography nr. 5
[18] See bibliography nr. 6

worked out in the BimSchG[19] in Germany and in the BAL[20] for the Netherlands. The require licenses depends on the amount of H_2 stored. However this also is the case for other goods that will most likely be already handled at the terminals.

5.3 Conclusions location requirements and spatial demands

Based on the traffic light method of paragraph 5.1 it can be concluded that the existing container terminals are the most suitable swapping locations for H_2-containers on the short and mid-term. The other two types of terminals have both advantages and disadvantages in different areas. It is therefore not possible to draw an unequivocal conclusion as to which type of terminal is the most suitable after the existing container terminals. That depends very much on the market developments and what type of users of transhipment facilities want to make use of them.

Due to the following (most important) reasons, the existing container terminals are most suitable as location for swapping H_2-containers:

- Most terminals are capable of handling dangerous goods. The terminal organizations are already prepared on handling dangerous goods. H_2-containers must be handled as dangerous goods (see 5.2), so the terminals can handle them without any necessary adjustments. The terminals already have their necessary permits, safety procedures, training of employees, knowledge, etc.
- Needed equipment and infrastructure is available: The container terminals have already the necessary and enough quay capacity, cranes, storage space, etc.
- Easily adopted in supply chain of container vessels: In the best case scenario, H_2-containers can be exchanged at the same terminal where the vessel has to load and unload its containers. In the unlikely event that a container vessel does have to exchange H_2-containers at another terminal, then both the terminals and the vessels are familiar with the procedures and actions at the terminal for loading and unloading containers. Also when containers have to be loaded and unloaded on a dry bulk vessel, it is a "normal" operation for the terminal organization. The dry bulk vessel has to call at another terminal, but this can be incorporated relatively easily in a planning. Logistical, financial and organizational impact of this are discussed in chapter 3.
- Growth of H_2-containers can be accommodated: In the highest scenarios in 2040, it is expected that in Rotterdam 347, in Duisburg 261 and at RheinCargo 132 full H_2-containers (300 bar) per port per day are needed. Each port has several container terminals. These volumes are therefore expected to be swapped at multiple terminals. The existing terminals are used to tranship much larger volumes and have therefore enough capacity to handle these volumes of H_2-containers.

[19] See bibliography nr. 2
[20] See bibliography nr. 14

Figure 5.1 Terminal locations in the three ports

Each individual container and dry bulk vessel operator has its own customers, destinations, routes and therefore their own logistic process. An optimal location of a container terminal for the swapping of H_2-containers can therefore not be determined unequivocally. It is different for every ship operator, highly depending on its specific logistical process. Because the optimal location is different for every organization, it is very important that there is a wide range of locations where H_2-containers can be swapped. There should be a broad coverage of possible swapping locations as possible.

On mid- and long term also other locations such as specific green field locations may become interesting as well as dry bulk terminals. This depends very much on the market development of users of H_2-containers and their and their need for swapping locations.

Because of the relatively high road transport costs for H_2-containers, locations close to container filling stations are desirable. The closer a filling location is to the terminal, the lower the transport costs and thus the better it is for the business case. In the beginning, inland shipping organizations will probably choose their swapping location based on an optimal mix of sailing time and costs and road transport costs for the supply and removal of the H_2-containers. With this in mind, new to be developed filling stations should consider locations near container terminals (as well as other H_2 users like trucks, buses, etc.).

Finally, also from safety perspective, H_2-containers can be swapped at existing container terminals that are already handling dangerous goods. For these terminals the extra hydrogen containers will not have a substantial impact on their current procedures. Also certain environmental licenses need to be acquired. This is similar to other goods that are already being transhipped on the current terminals.

Other terminals will need extra spatial requirements and investments due to the extra safety requirements as well as licenses that are needed for dangerous goods.

Chapter 6 Demand scenarios and effect on spatial & safety demands

6.1 Introduction demand scenario

The aim of this chapter is to divide the total projected hydrogen demand (RH2INE demand study (sub-study 1.1c) over the main port areas in the Rhine area, for the years 2030 and 2040.

Studies indicate that "Inland shipping companies or operators bunker at the most convenient operational moments." Another observation is that "Inland shipping companies bunker mainly at the start of the trip. Another option is bunkering during sail, preferably during the day and at a bunker station along the river."[21] Important drivers for selecting a location to bunker are also (according to the same study):

- The sailing area of the vessels, where detouring is not an option for ship owners.
- ADR routes towards the bunker location, since hydrogen containers have to be transported via a road route to the unloading/loading location.

In this chapter one intermediate scenario to divide the total demand over the port has been chosen.

6.2 Input information

Various sources have been used as input for this demand scenario. The most important studies used include the RH2INE Programme: Sub-Study 1a: Safety Framework Conditions 'SuAc 1.1c Hydrogen Demand Study' (DNV-GL, 2020) and the 'RH2INE Final report'. The total demand that was calculated in the pre-study includes all vessels that (partly) sail the Rhine route, so also includes f.i. Rotterdam – Amsterdam and Rotterdam – Antwerp traffic.

The projected demand for hydrogen is between 5.000 and 48.000 tons in 2030 and 10.000 and 104.000 tons in 2040.

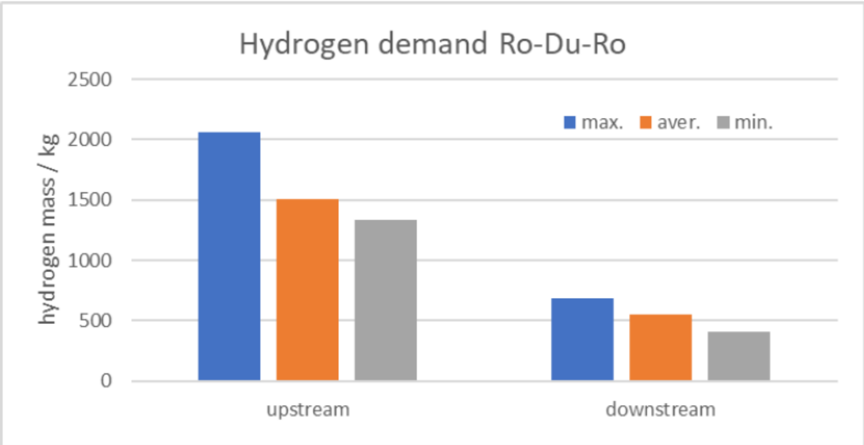
Table 6.1 Volume scenarios of demand study (source sub–study 1.1c, DNV-GL)

Year	Low (tons)	Medium (tons)	High (tons)
2030	5.000	18.000	48.000
2040	10.000	36.000	104.000

[21] Source: Breakthrough LNG Deployment in Inland Waterway Transport - Activity 5 Study into best locations for LNG bunkering stations & Activity 6.1 Comparison study on refilling of the LNG bunker station by tanker truck and by bunker barge, ENGIE LNG Solutions and Pitpoint, 2017.

Sub-Study 2 (ZBT and Energy Engineers, 2021) showed that a reference ship (container ship of 135 meter x 14,20 meter, 421 TEU) would need 1,8 to 2,8 tons of hydrogen to make the round-trip Rotterdam-Duisburg, of which the largest share (70%) would be consumed upstream. One vessel would in that case use about 400 tons of hydrogen per year, based on 3 of this 'typical' round-trips a week (24/7 operation). Calculations in this chapter have been based solely on this same reference ship. Also this standard round-trip Rotterdam – Duisburg has been assumed representative for all traffic.

Figure 6.1 Projected hydrogen demand for the reference ship on the round-trip Rotterdam – Duisburg (ZBT and Energy Engineers, 2021)



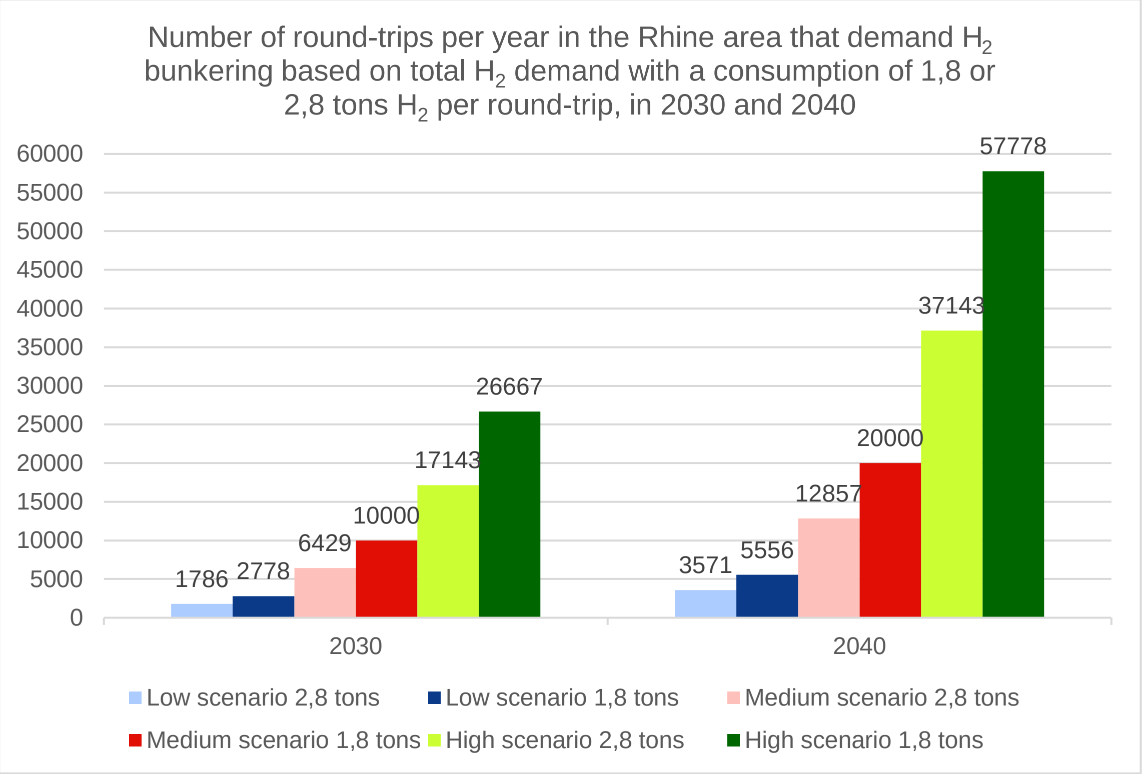
For allocation of the projected hydrogen demand volume to various areas, BIVAS data (2018) has been used. BIVAS is based on data of vessel traffic from IVS-90 (Information and Tracking System for Waterway Transport) and is published by Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management).

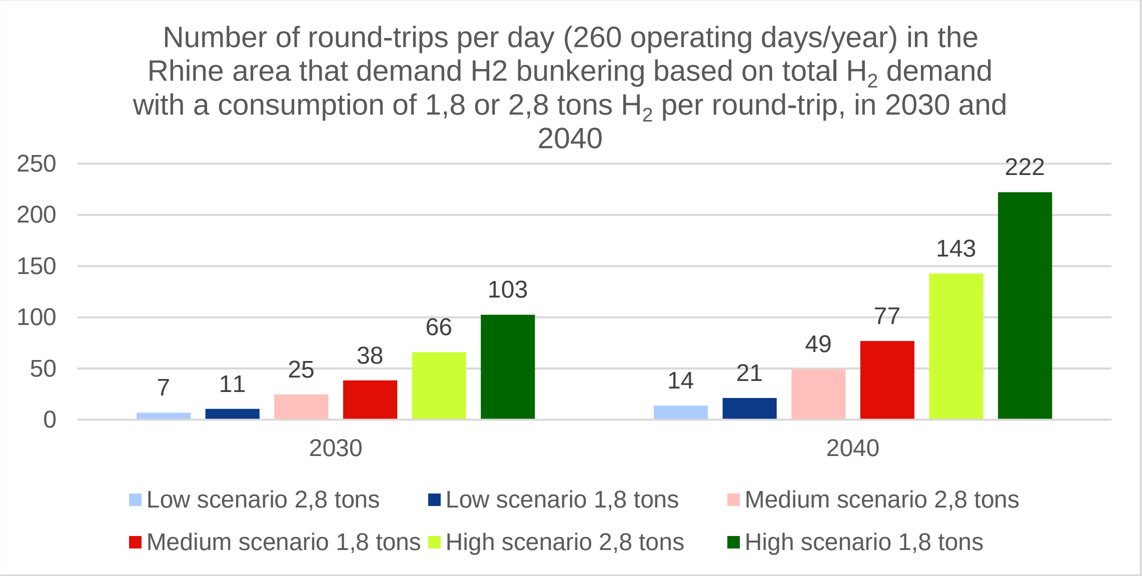
6.3 Scenario chosen and assumptions in the demand scenario

From the total hydrogen demand and the typical consumption of 1,8 to 2,8 tons per roundtrip, the total number of roundtrips per year that demand hydrogen bunkering can be calculated. In 2030 1.786 – 26.667 roundtrips are expected to need bunkering (swapping containers). If vessels do a round-trip Rotterdam – Duisburg with 1 bunker event, 1.786 – 26.677 are needed in 2030. In 2040 3.571 – 57.778 bunker events can be expected. On a 52 week, 5 days per week operation, in 2030 7 – 103 round-trips need hydrogen bunkering per day and in 2040 14 – 222 round-trips. If vessels would bunker twice on the route, this number doubles, etcetera. The pre-study by ZBT and Energy Engineers indicates that this could be the case if for instance a ship does not have the capacity to carry all the containers needed for the round-trip.

The variables in these calculations are:
- Hydrogen demand low – medium – high scenario.
- Consumption of either 1,8 or 2,8 tons of hydrogen per round-trip Rotterdam – Duisburg.
- 260 operating days/year to convert yearly demand to daily demand.

Figure 6.2 Number of round-trips per year and day that demand H_2 bunkering, in 2030 and 2040





To be able to divide the demand over the port areas, the number of vessel passages on specific counting locations have been investigated (see below) (source BIVAS (2018)). On top, a number of assumptions have been done:

- The demand is divided over dry bulk and container vessels equally, Hydrogen penetration is assumed to be an equal share for both dry bulk and container vessels. There is no reason from the pre-studies to deviate from this, since the total H_2 demand has been calculated out of these segments as well. A sensitivity analysis on this topic has been added to this chapter in the last paragraph.
- Vessels that navigate (partly) on the Rhine route are in scope (e.g. also vessels between Rotterdam – Antwerp and vessels between Nordrhein-Westfalen – Antwerp are in scope). There is no reason from the pre-studies to deviate from this, since the total H_2 demand has been calculated including this traffic as well.
- To divide the projected demand over the major (port) areas along the Rhine the following division has been made:
  - for Rotterdam the vessels that pass the counting location on the Oude Maas (Hoogvliet/Spijkenisse) and Nieuwe Maas (Rotterdam city) have been included;
  - for Duisport the vessels that pass the counting location just north of Duisburg have been included;
  - for RheinCargo the vessels that pass the counting location between Düsseldorf and Köln have been included;
  - for Antwerpen / North-Sea Port Area the vessels that pass the counting location on the Volkeraksluizen have been included;
  - for Amsterdam Area the vessels that pass the counting location at the Amsterdam-Rijnkanaal near Tiel have been included (relevant for Rhine traffic);
  - for Upper Rhine the mean of vessels that pass the counting location between Darmstadt and Mannheim and Mannheim and Karlsruhe has been included.
- The forementioned counting locations are assumed to be representative for the respective areas. Other areas are marginal origin-destination areas and are not included.
- In the next step the proportions of vessel traffic are assigned to the forementioned areas. Other areas are – in the scenario – assumed to be not relevant due to lower volumes, but could also demand hydrogen in the future based on existing infrastructure and logistics decisions.
- Exact origin – destination relations of vessels are unknown. All passages of dry bulk and container vessels that pass a counting location on the Rhine are assumed to be relevant. However, it is known and it can be derived from the current practice and interviews that bunkering is preferred in the port areas (that are also origin – destination areas). The demand scenario is thus concentrated on the main origin – destination regions in the Rhine area.

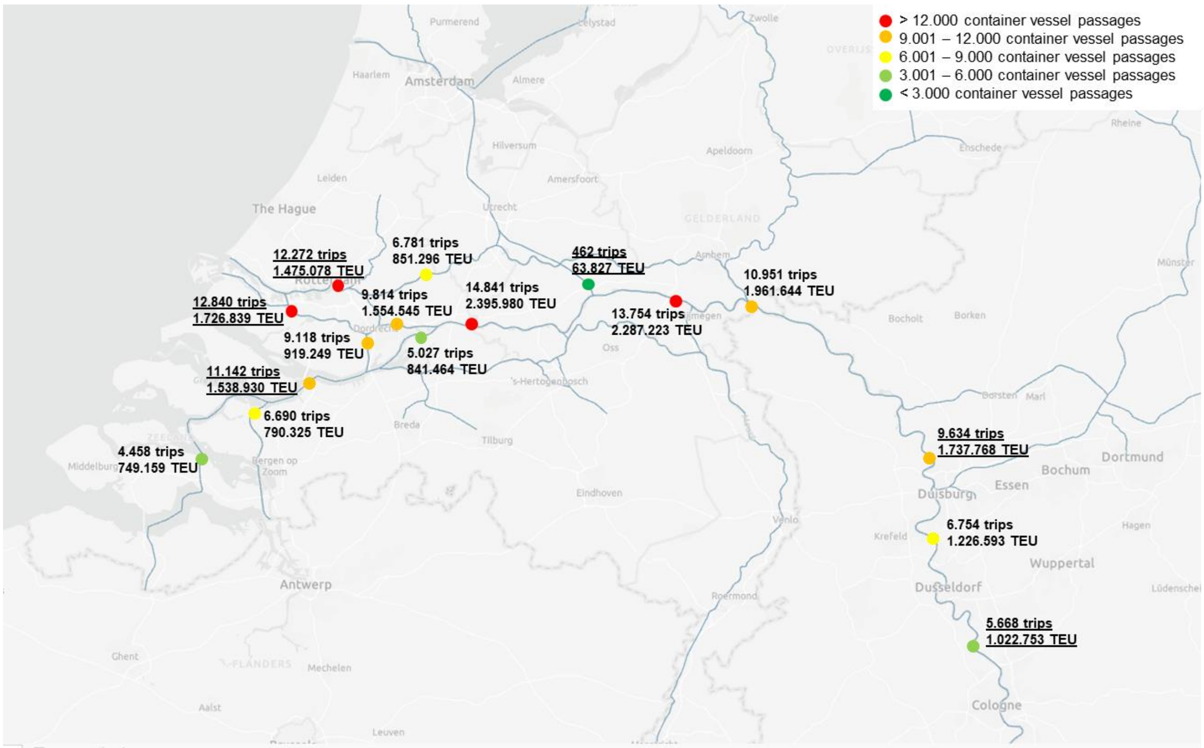
6.4 The Demand Scenario

The number of vessels (round trips) per day that need hydrogen bunkering are (based on 52 weeks, 5 days per week).

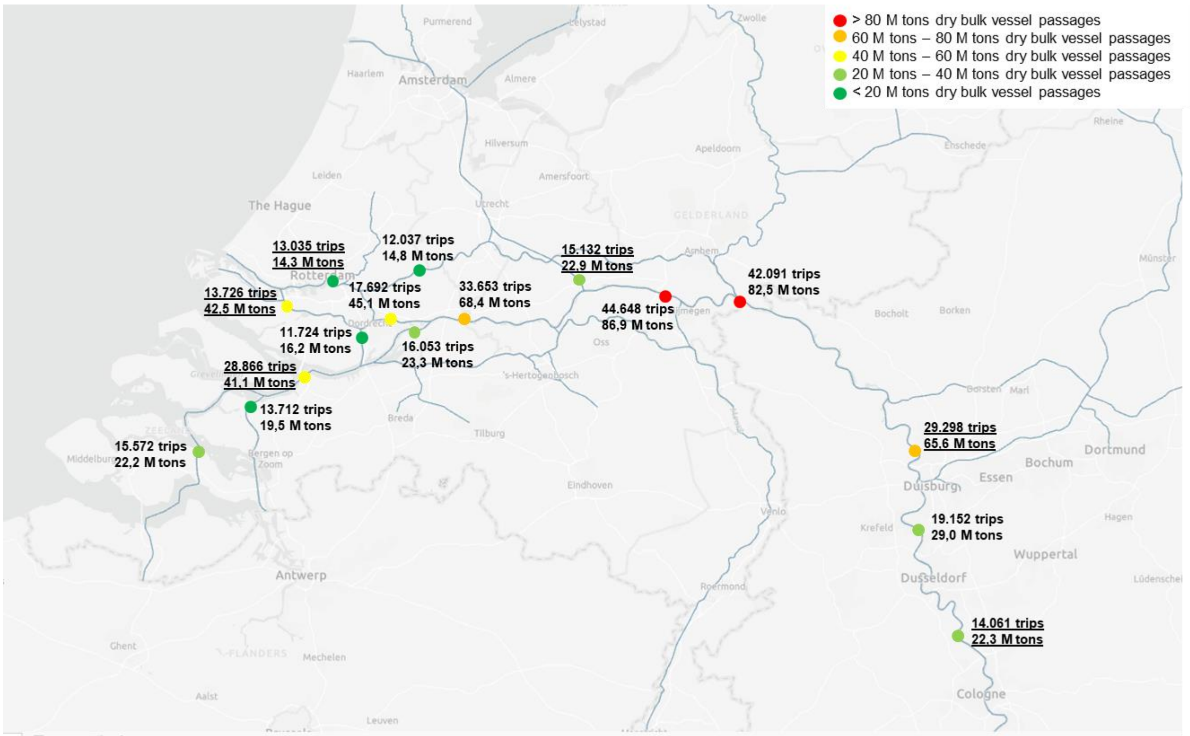
Vessels per day	Low (tons)		Medium (tons)		High (tons)	
Fuel consumption H_2 per round trip (tons)	1,8	2,8	1,8	2,8	1,8	2,8
2030	11	7	38	25	103	66
2040	21	14	77	49	222	143

The number of container and dry bulk vessel passages on counting locations have been displayed in the figures below. The forementioned counting locations for the various areas have been underlined.

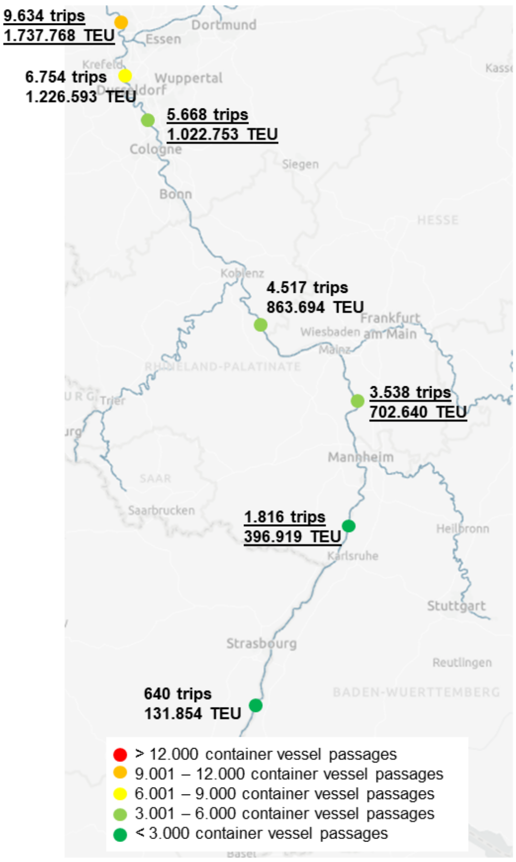
Figure 6.3 Container and dry bulk vessels on counting locations along the Rhine area

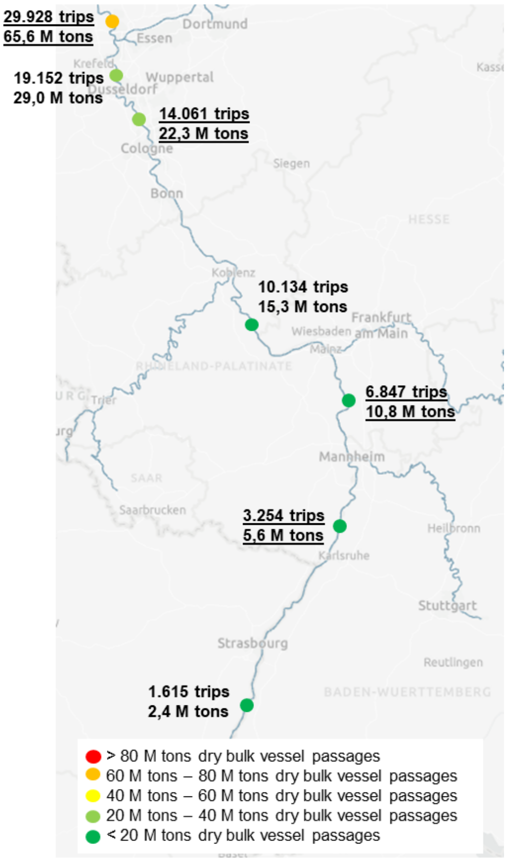


Source: BIVAS, 2018 data



Source: BIVAS, 2018 data

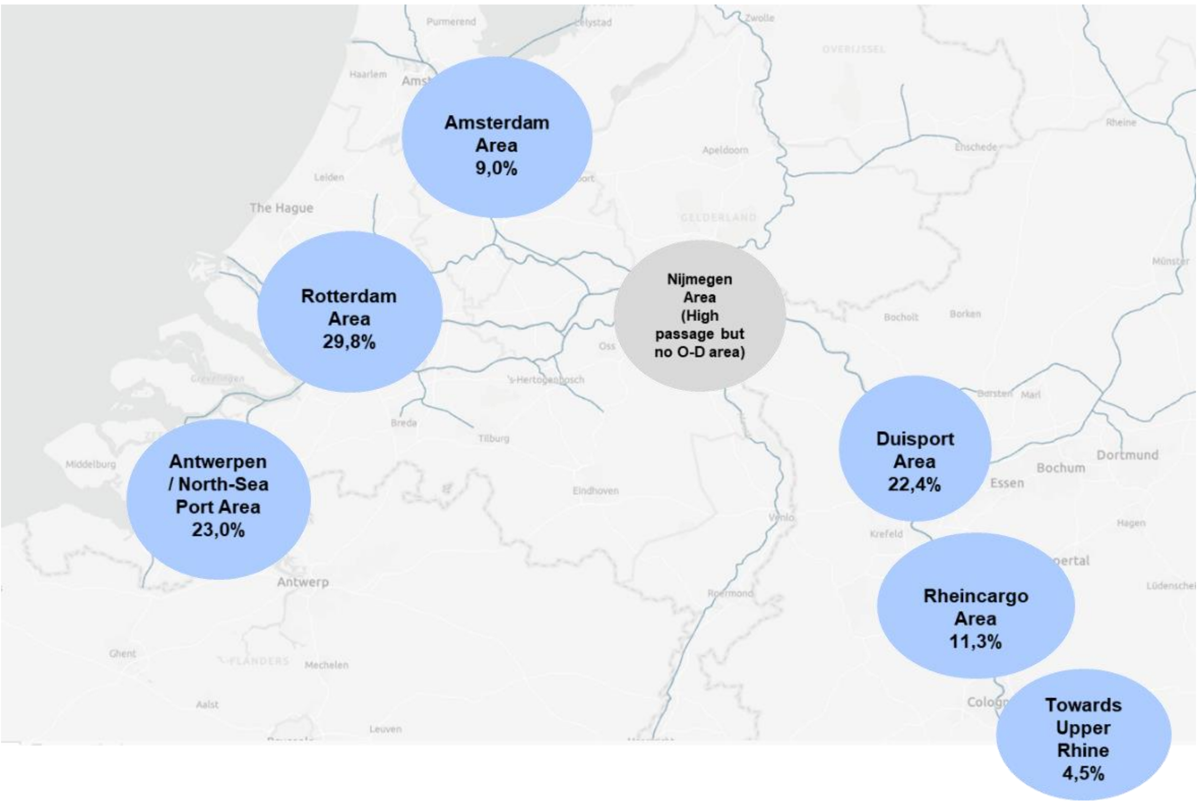




Source: BIVAS, 2018 data

Based on the ratio between the locations, the hydrogen demand for each area has been calculated. The projected demand for the Rotterdam Area is the highest and for the Upper Rhine region the lowest.

Figure 6.4 Projected share in demand for H_2 from container and dry bulk vessels in O-D areas based on vessel passages



The projected hydrogen demand is the highest for Rotterdam and is estimated between 1.490 and 14.304 tons for 2030. This amount is roughly doubled towards 2040. Other port areas have lower projected hydrogen demands. This demand is expected to be affected by:

- Logistics strategies of ship owners and terminal organizations.
- Market developments in hydrogen supply (which can lead to different cost structures in different locations and varying logistics costs).
- Decisions based on financial grounds (actual costs of filled H_2-container in different locations).
- Decisions on the actual number of H_2-containers carried on board a vessel, that reduce the range of the vessel and that could potentially lead to the need to swap containers more frequently than was assumed in earlier pre-studies. In that scenario an extra stop would be necessary anyway. Swapping containers in high passage but no O-D areas (f.i. Nijmegen area), would then be more likely or even necessary.

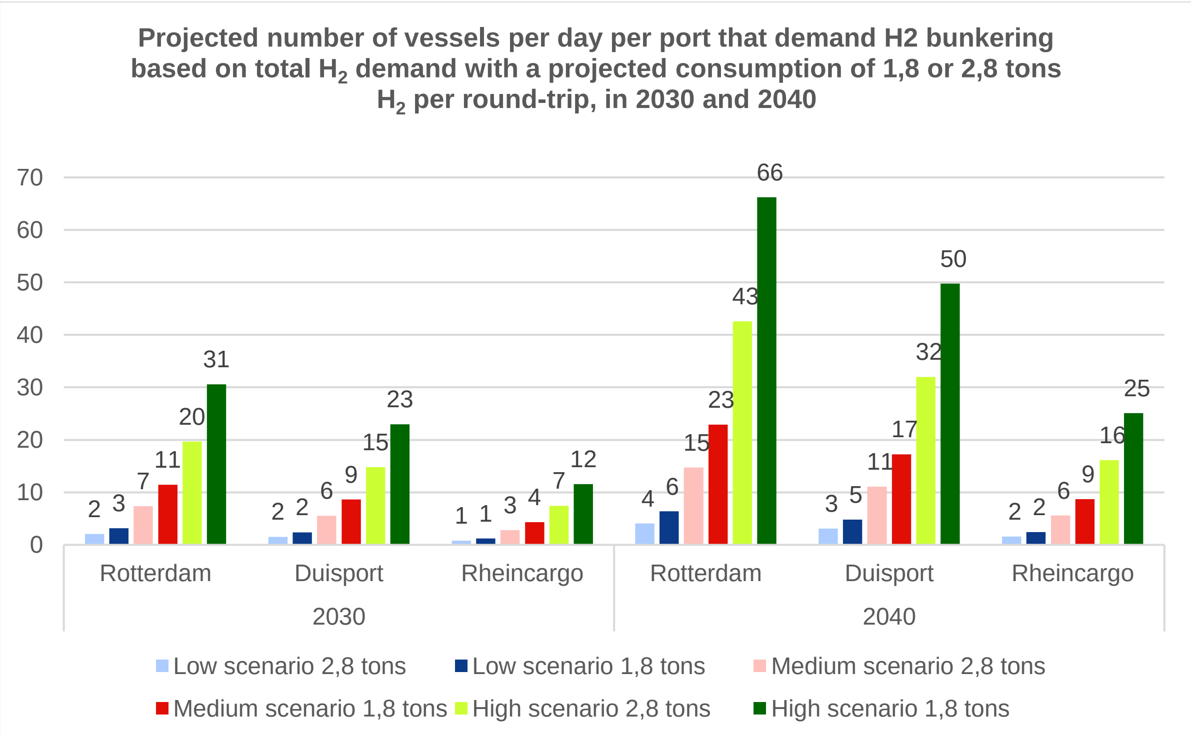
Three port areas (Rotterdam, Duisport, RheinCargo) are in scope for this study and specific demands have been elaborated further on the next pages.

Table 6.2 Projected hydrogen demand in various port areas in 2030 and 2040

Year	Low (tons)	Medium (tons)	High (tons)	
2030	**5.000**	**18.000**	**48.000**	
Rotterdam Area	1.490	5.364	14.304	In scope
Duisport Area	1.120	4.032	10.752	In scope
RheinCargo Area	565	2.034	5.424	In scope
North-Sea Port / Antwerpen	1.150	4.140	11.040	Out of scope
Amsterdam Area	450	1.620	4.320	Out of scope
Upper Rhine	225	810	2.160	Out of scope
2040	**10.000**	**36.000**	**104.000**	
Rotterdam Area	2.980	10.728	30.992	In scope
Duisport Area	2.240	8.064	23.296	In scope
RheinCargo Area	1.130	4.068	11.752	In scope
North-Sea Port / Antwerpen	2.300	8.280	23.920	Out of scope
Amsterdam Area	900	3.240	9.360	Out of scope
Upper Rhine	450	1.620	4.680	Out of scope

Based on 260 operating days per year, the projected number of vessels per day that demand hydrogen bunkering is for Rotterdam 2 to 31, for Duisport 2 to 23 and for RheinCargo 1 to 12 in 2030. The number of bunkering events could be higher in case vessels bunker multiple times during a round-trip.

Figure 6.5 Projected number of vessels per day that demand hydrogen in port areas, 2030 and 2040



The pre-study performed by ZBT and Energy Engineers (2021) has shown that a 300 bar cylinder type IV container can carry 371 kg of hydrogen and a 500 bar cylinder type container can carry 518 kg of hydrogen. This would mean that – based on total demand – in 2030 a total of 13.477 to 129.380 filled containers (300 bar, without spare containers) would fulfil the total demand. With higher pressure, the total demand of filled containers would decrease.

Table 6.3 Total H_2 filled container demand, per year based on total demand

300 bar, 20 ft containers		
Capacity	371 kg H2	0,371 tons H2

Year, 300 bar	Low	Medium	High
2030	13.477	48.518	129.380
2040	26.954	97.035	280.323

500 bar, 20 ft containers		
Capacity	518 kg H2	0,518 tons H2

Year, 500 bar	Low	Medium	High
2030	9.653	34.749	92.664
2040	19.305	69.498	200.772

Based on the 1,8 – 2,8 tons hydrogen consumption per round-trip Rotterdam – Duisburg, a vessel would need 5 to 8 300 bar cylinder type IV hydrogen filled 20 ft containers (without spare). Based on 500 bar 20 ft containers the amount of containers needed would decrease to 4 to 6, depending on the consumption. The actual one or other used pressure (300 – 500 bar) and consumption (1,8 – 2,8 tons) determine the actual number of bunkering events (whether or not a second bunkering event is needed during a round-trip).

Table 6.4 Number of filled hydrogen containers (without spare) needed for round-trip Rotterdam – Duisburg

	1,8 tons consumption	2,8 tons consumption	
Upstream consumption	1,26	1,96	tons of hydrogen
Downstream consumption	0,54	0,84	tons of hydrogen
300 bar	**5**	**8**	filled H_2 containers
Upstream consumption	3,4	5,3	filled H_2 containers
Downstream consumption	1,5	2,3	filled H_2 containers
500 bar	**4**	**6**	filled H_2 containers
Upstream consumption	2,4	3,8	filled H_2 containers
Downstream consumption	1,0	1,6	filled H_2 containers

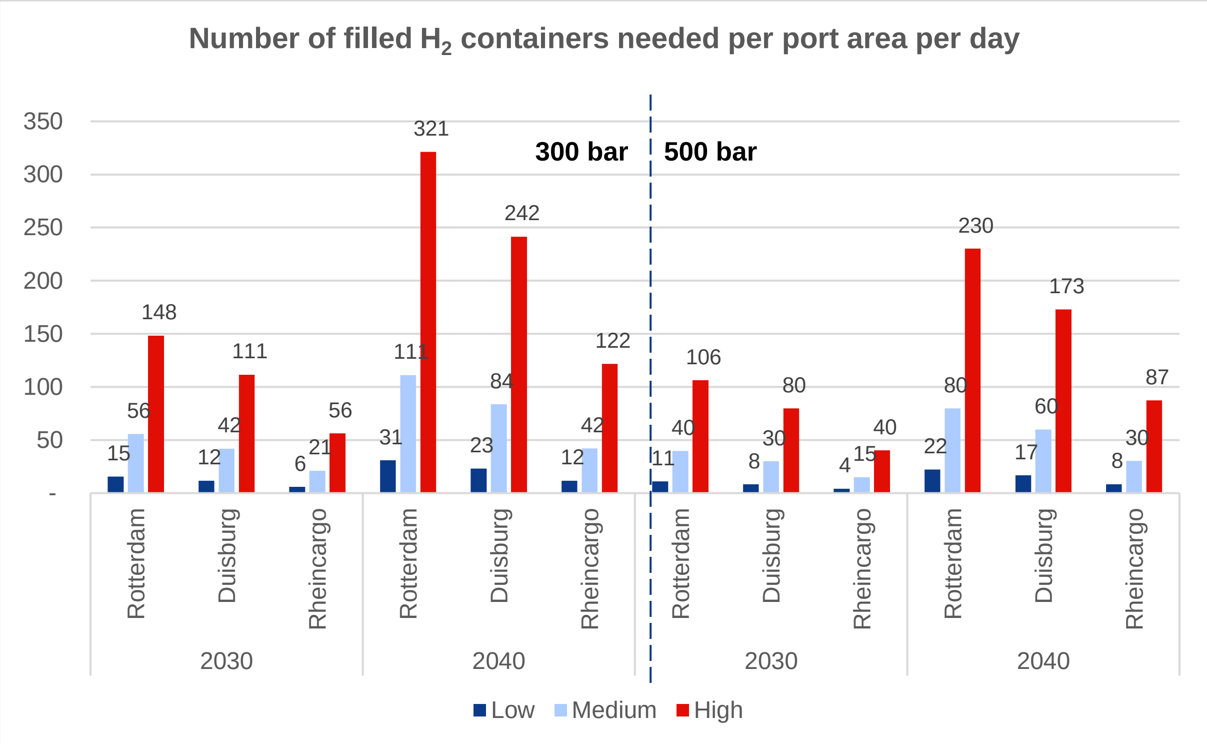
Based on the demand scenario and the total projected number of filled hydrogen containers needed, in 2030 an average of 11 to 148 filled hydrogen containers per day are needed in the Rotterdam area, depending on the total demand and the pressure of the hydrogen (300

– 500 bar); in Duisburg/Duisport area this number is 8 to 111 containers and in the Rhein-Cargo area 4 to 56.

The containers will be handled on various terminals in a port area, depending on the logistic requirements of inland shipping, meaning that the number of containers of each port will be divided among several terminals.

The number of hydrogen containers is based on a capacity of 371 kg H_2 for a 300 bar Class IV container and 518 kg H_2 for a 500 bar container and on 260 operating days per year.

Figure 6.6 Number of filled hydrogen containers needed per area per day (without spare containers)

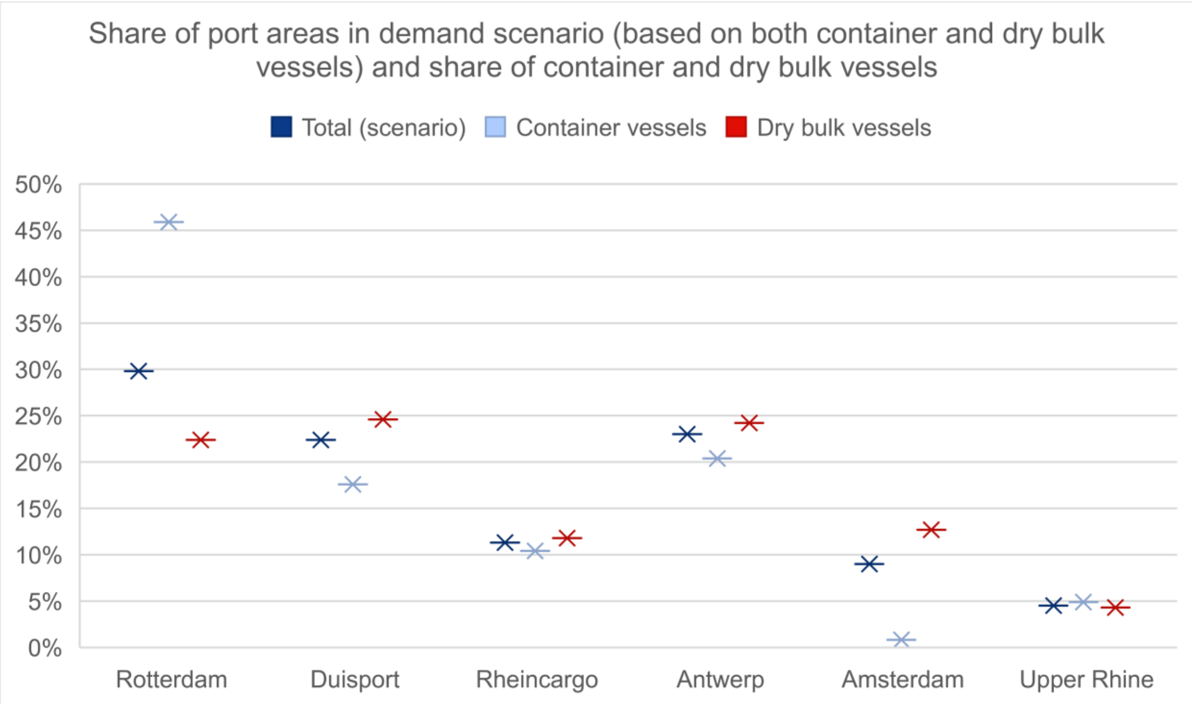


6.5 Sensitivity

This chapter has described one (average) demand scenario, based on input from previous studies and other input and assumptions which are described earlier in this chapter. One important element of the scenario is that the hydrogen penetration rate for container and dry bulk vessels has been set equally. A sensitivity analysis has been done for this element (see figures below). The most important conclusion is that if the penetration rate for container vessels in the future will be higher than for dry bulk vessels, the hydrogen demand for the Rotterdam area will be substantially higher than in the demand scenario chosen and in the other regions lower (especially for Amsterdam, but also for the Duisport area). If the penetration rate for dry bulk vessels will be higher than for container vessels – which is assessed less realistic, based on the interviews – the hydrogen demand for Rotterdam will be somewhat lower than described and for the other areas higher.

Figure 6.7 Chosen share in demand for H_2 from container and dry bulk vessels in demand scenario and share of container and dry bulk vessels in port areas (BIVAS, 2018).

Area	Total (scenario)	Container vessels	Dry bulk vessels
Rotterdam	29,8%	45,9%	22,4%
Duisport	22,4%	17,6%	24,6%
RheinCargo	11,3%	10,4%	11,8%
Antwerp	23,0%	20,4%	24,2%
Amsterdam	9,0%	0,8%	12,7%
Upper Rhine	4,5%	4,9%	4,3%



Another important variable is the actual number of H_2 containers that will be carried on board a vessel. For instance, if a lower number of containers would be carried compared to the reference ship. This would affect (reduce) range and could potentially lead to the need to swap containers more frequently than was assumed in earlier pre-studies. In that scenario an extra stop along the Rhine would be necessary anyway. Swapping containers in high passage but no O-D areas (f.i. Nijmegen area), would then be more likely or even necessary.

Chapter 7 **Long-term bunkering stations**

In this chapter, a qualitative description is made of the possible effects of switching from container swapping to future scenarios for example, bunkering with hoses.

The demand study in chapter 6 shows that on the longer term the demand of H_2 increases rapidly. With increasing demand in both the inland shipping and other modalities more refilling stations will be built by hydrogen suppliers. Hydrogen suppliers have already mentioned these plans for the future. The containers can still be filled and the trucks can be used but at some point this will not be the most efficient method. Especially road transport from the filling station to the terminal and the return trip with the empty containers will become a bottleneck logistically as well in cost (also caused by the limited storage time).

For the mid-term the previous studies concluded that LH_2 would be an alternative for compressed H_2. This would be an improvement in energy density. LH_2 is an established form of energy storage. Containers for LH_2 are available but there are relatively small amount of LH_2 production sites. Only four LH_2 plants exist in Europe at this moment with a total production of approx. 30 t/d. Only the plant in Rotterdam with approx. 6 t/d hydrogen production is located directly near the Rhine. Permanent LH_2 tanks would likely be installed on board and refuelling would have to be done by hose. This would require the development of bunkering with a hose at a bunkering station. Alternatively, this could be done by truck-to-ship bunkering which is also applied in the LNG sector. This scenario will result in a relatively decreasing number of locations offering compressed H_2. Also the infrastructure and safety measures onboard will have to be changed. The bunkering cannot be combined with container transhipment anymore. The risks of LH_2 as a cryogenic liquid are different to compressed H_2. LH_2 bunkering stations would require a revised risk analysis.

Also, if large scale local storage is implemented (as would be the case when switching from truck to pipeline delivery), extensive safety measures are required and (more) extended safety distances are mandated. LH_2 requires a continuous blow off system to keep the H_2 cooled. This introduces additional economic losses, safety risks and emissions.

There is practical experience with delivery stations of the LNG sector and for LH_2 there is experience in road transport. This experience is codified in the Dutch guideline (PGS33-2[22] and PGS35)[23].

A long-term scenario (10-20 year) would be the use of hydrogen carrier technologies. But technical development is still required for these techniques to become feasible and cost-effective. Examples of hydrogen carriers are sodium borohydride, LOHC (various chemicals) and methanol. They are all promising in different degrees with regard to safety, availability or existing supply logistics. Each will have the potential to allow the use of the more conventional (low pressure) bunkering methods. However, the availability of the carriers is limited. On

[22] See bibliography nr. 11.
[23] See bibliography nr. 12.

board the equipment has to be changed, because the carriers also have a waste stream that have to be stored and returned (possibly with the exception of methanol). This will create extra complexity onboard and additional costs in general. These hydrogen carrier technologies use different substances with different properties and will need to be assessed in individual detail both in terms of safety and environmental standards.

Each of the scenarios will require investments both onshore and onboard. It seems unlikely that a vessel will be adapted multiple times. So vessels that are early converters will still need to operate with the swappable containers in a long-term scenario. This will also require that the infrastructure created during the short- and mid-term scenarios will have to be kept operational.

The new technologies to be used in the long-term scenarios come with their individual additional safety, environmental and logistic challenges. The technologies are not yet mature enough to assess and compare the risks and codify standards, but mitigating measures can be applied (using existing technology) that keep the safety and environmental risks at an acceptable level. It is expected that the short-term solution of using pressurized H_2-containers will be kept operational in the long-term scenarios, although possible on a relatively diminishing scale.

Chapter 8 **Investments needed**

8.1 Introduction

The RH2INE design study already provides useful insights in the additional cost of container swapping. This cost analysis was, however, carried out from a TCO (Total Cost of Ownership) perspective and mainly covers the shipper perspective. On the other hand, the TCO could only be calculated by taking into account the various investment cost in the supply chain and therefore also covers other parts of the supply chain. Additionally, a Cost Benefit Analysis has been carried out in the design study, in order to compare the CO2 reduction costs with the external costs of emissions.

Because many investments have already been described in the design study, this chapter describes any additional issues in relation to investments in a qualitative way and discusses the issues that have been raised during interviews with market actors. These issues are linked to the differences in possible supply structures for hydrogen containers and the implications for the business case. Where differences can be identified between the design study and the interview outcomes of this study, these differences are described.

8.2 Inland vessels

The preferred configuration in terms of number of containers and location on the vessel differs per ship due to the differences in technical feasibility and operational characteristics. This means that the required investments and cost impacts will differ per individual vessel. As already described in the chapter on logistics (Chapter 4), shippers will aim to find the balance between use of space on board on the one hand and frequency of bunkering on the other hand. A higher number of hydrogen containers on-board means additional loss of income due to lost cargo space, but a lower number of terminal visits for swapping hydrogen containers. At container terminals, shippers are likely to pay additional handling cost for the containers filled with hydrogen. The height of these additional handling cost may depend on whether they are a regular customer and depends on whether swapping hydrogen containers is combined with loading and unloading of other containers.

Empty H_2-containers will probably not be completely empty at the moment of swapping most of the time. Therefore, a system is needed which determines the volume of remaining hydrogen and which compensates the ship operator for the hydrogen not consumed (ZBT and EE, 2021).

Overall, the additional cost for ship operators using H_2 as a fuel could make inland shipping less competitive[24] and might result in a modal shift from inland shipping to other modes of transport.

8.3 Container terminals

Container terminals do not need to invest in transhipment equipment (in contrast to dry bulk terminals). Container terminals, however, earn the same amount of money for the transhipment of hydrogen containers (and other containers with dangerous substances) as for the transhipment of ‘normal’ containers (~€40 per move), but the efforts and costs can be higher (depending on the terminal): reserving space for a separate container stack, moving the container to the dangerous substances stack (which might be further away, again depending on the lay-out of an individual container terminal) and higher risks (related to damaging of the container). From this perspective, it may be hard to develop a business case for the container terminal. Besides the handling at a terminal, additional planning efforts might be necessary, not only for the arrival of vessels, but also for the handling of containers (how to combine regular containers with the hydrogen filled containers). With respect to this last point, environmental requirements and safety aspects are likely to be decisive.

Dry bulk terminals are not likely to invest in cranes to handle containers, because the demand for swappable hydrogen containers is still lacking and alternative refuelling options for hydrogen are expected to become viable when hydrogen supply and demand increase. New container terminals at green field locations are not expected on the short term either. Of course, this also depends on the developments in the container market and on the extent to which existing container terminals will have sufficient spare capacity for hydrogen swapping. Specific ‘green quays’ where multiple alternative fuels are offered are an option: the business case will be better compared to dedicated container swapping locations at green field locations, because multiple fuels/energy carriers are combined and thus more vessels can be served. For ship operators, this could increase cost, because container handling and swapping can probably not be combined at these locations.

8.4 Hydrogen container transport

The transport of hydrogen containers by truck adds to the hydrogen price to such a degree that the business case for shippers becomes significantly worse. This also holds for additional transhipment (additional terminal visits or moving to a separate quay for hydrogen container swapping). High costs as result of the transport of hydrogen containers by trucks can be reduced by minimizing the transport distance. In case a third party will become responsible for the container distribution from filling stations to the various terminals additional cost could arise from this extra stakeholder added to the supply chain. On the other hand, such a

[24] This also depends on the introduction of any policy measure to make the use of fossil fuels more expensive.

stakeholder could contribute to the efficiency and optimization of container distribution and thus to cost reductions. However, in a situation with a low hydrogen demand and only a few filling stations and terminals on the Rhine corridor, opportunities to reduce transport distances will be limited.

8.5 Ownership of containers

When moving to a swappable hydrogen container system for inland waterway ships, the investment in the hydrogen containers forms the largest investment. The design study provides an indication of the purchase cost: the cost for a 20ft-container (with different pressures and cylinder types) varies between 150,000 to 380,000 euro with the high end of the range representing a Type IV 500 bar container. If a shipper owns the hydrogen containers, he needs to pay the costs associated with the maintenance and inspection as well. Moreover, if the shipper should also arrange for the availability of filled containers at the right place and time, there are additional costs for planning, transport of the containers and the purchase of spare containers. From the interviews the conclusion can be drawn that individual ownership of containers is unlikely and lease concepts / ownership of the containers by hydrogen suppliers or an additional third party are more preferred for reasons of safety, sharing of risks and responsibility, and operational efficiency. This might result in a lease system or pay per use system where all additional cost will be included in the hydrogen price (per kg), similar to battery technologies, or paying of additional fees for the rent of a container. There is currently no consensus on how a container pooling system should be organized and how it should function in practice. For example, a pool can exist of one size of containers or multiple sizes (both 20ft and 40ft). Whether pool concepts will be realized depends on the profitability of the business case in combination with the ability to reach agreement on organizational aspects (mainly on insurance issues and safety risks).

8.6 Filling stations

As indicated before, filling stations will be realized on or near the hydrogen production sites. Compared to current filling stations for tube trailers (operating at 200 bar, which is the current standard), the compression systems need to be upgraded (to 300 and/or 500 bar). Although both 300 bar and 500 bar have been mentioned by the interviewed parties several times, 300 bar is expected to be the preferred option for the coming years.

From the interviews it became clear that hydrogen suppliers currently choose to fill containers at a relatively low speed. The filling speed is an important economic factor: higher filling speeds require additional cooling and thus higher energy cost. The current low demand allows for a lower filling speed and less cooling, keeping cost down. If demand increases, and a higher filling speed increases the number of containers that is filled per day, the additional income is likely to outweigh the higher cost of cooling.

Overall, from the interviews it is concluded that hydrogen producers are likely to respond to market demand by investing in filling stations and they are also willing to invest in containers. This business concept is not completely new to them and it is quite in line with the current hydrogen distribution system using tube trailers. However, the availability of hydrogen for filling containers for inland shipping will depend on the development of hydrogen production capacity, hydrogen demand from other sectors, and the willingness to pay for hydrogen from each of the sectors.

8.7 Type of hydrogen

In the design study the use of green (renewable) hydrogen was an important assumption. Within our sub-study green hydrogen was not seen as an important prerequisite by the interviewed hydrogen suppliers. Where the transport sector has focused on 100% renewable hydrogen from the start, the energy sector more often mentions a gradual transition from fossil to 'blue' to renewable hydrogen. An aspect which has not been taken into account in the design study is the potential contribution of renewable hydrogen applied in inland shipping to the renewable energy obligation in transport. If renewable hydrogen can be counted towards the targets, the business case of renewable hydrogen will improve substantially. Relevant developments linked to renewable obligations are the development of a certification system for hydrogen and the specific calculation methodology and requirements for the link between production and supply. The Dutch government is currently working on the implementation of the Renewable Energy Directive II, including the role of inland shipping and the use of hydrogen in transport. If the national implementations in Germany and the Netherlands differ, it might make one of those countries more attractive than the other country and in that respect might impact the location of bunkering.

8.8 Long term investments versus an intermediate solution

Swappable containers appear to be the way forward for stakeholders which are keen on switching to hydrogen on the short term. However, other stakeholders appear to await the commercial application of hose bunkering, which will be favourable for large scale hydrogen bunkering and enable faster refuelling. Some stakeholders believe this type of bunkering will 'win' on the long term and will result in higher investment security. In the coming years, this might be an important reason for limited investments in container swapping along the supply chain, as market parties consider the risks of stranded assets to be too high. For example, dry bulk container terminals are not likely to invest in cranes.

8.9 Conclusions

Based on this analysis it can be concluded that investment costs are mainly related to investment in containers. The additional costs of certification, inspection and maintenance of containers and the operational costs related to container distribution will be incorporated in the hydrogen price. Other costs are mainly linked to the operational and organizational aspects of container swapping at container terminals and the vessel itself. There are, however, many uncertainties, such as the actual demand for swappable hydrogen containers in the coming years. Also, there is still limited experience with container swapping. Therefore, additional investments cannot be ruled out completely.

Chapter 9 Conclusions and recommendations

This “RH2INE location study” analysed possible locations where H_2-containers can be swapped from land to vessels and vice versa. Should specific swapping locations be developed or are existing locations suitable? Als the effects of swapping hydrogen containers on logistics is compared to diesel fuel (effects include dealing with H_2-containers, effect on operations, planning, training, but also how containers must be supplied and filled and the effect on filling stations). Finally, the impact on investments is examined. Based on this analysis, the following conclusions and recommendations are defined:

- A swappable compressed hydrogen container system is useful and possible as a short-/mid-term solution to initiate the use of hydrogen in inland shipping:
  - Container handling infrastructure and organisations are already available: In each port multiple container terminals are existing. Most of these terminals are already handling containers with dangerous goods and are therefore allowed to also handle hydrogen containers. These organisations are also trained in handling dangerous goods and have the right permits. Also the capacity of these terminals is high enough to handle the H_2-containers now and in the future.
  - Container swapping fits well with existing logistics operations of terminal organisations and inland shipping organisations: Hydrogen containers can be handled as any other dangerous goods containers. Most of the container terminals are familiar with handling of these containers. The same applies to inland shipping organisations. Dry bulk organisations are not (yet) familiar with this. For them, training and adaptation of their organisation and processes will be necessary.
  - Main challenges (and focus for next steps) are:
    - ➢ development and scaling up number of available H_2-containers: In order not to disrupt logistics too much, it is important that hydrogen containers are available at the moment they are needed by an inland vessel. The more vessels that run on hydrogen, the more containers are needed, in order to make the containers available flexibly and on time. H_2-containers are however expansive. Scaling up the number of H_2-containers therefore requires large investments that must be made some time before sufficient turnover can be generated;
    - ➢ standardization of the H_2-containers: In order to make the exchange and inspection of containers as simple as possible in the future, it is important that the technical design of H_2-containers is standardised as much as possible. This also increases the flexibility of using the containers (even also when the containers may be used by other modes of transport in the future). However, standardisation requires good cooperation between all parties involved and perhaps also some frontrunners who take this up;
    - ➢ expansion of the number of H_2-vessels: The number of H_2-containers and the number of H_2-vessels depend on each other. H_2-vessels are served by a good price for H_2. An important cost item is container rental/leasing costs. The larger

the container market, the lower the cost per container. However, the number of H_2-containers that is made is dependent on the need for these containers. This need, in turn, depends on the number of H_2-vessels. Investment in the expansion of the number of H_2 vessels is therefore necessary;

- costs (H_2, H_2-containers and H_2-vessles). Hydrogen is at this moment still an expensive fuel. To be able to have profitable business cases for the various players in this supply chain, it is important that the market grows in total and that the unit costs (tons of H_2, containers, vessels) fall sharply.

- Effects on logistics
  - The flexibility in container swapping (and potentially creating a container pool) depends on standardization of the H_2 containers and number of container terminals offering (the handling of) containers. The use of own container designs might limit this flexibility.
  - Not all container terminals seem to be a good location for container swapping. Deep sea container terminals are not a viable option, while smaller (inland) container terminals are more likely to be able to meet the specific demands for container swapping. Differences exist between the different types of container terminal (separate quay or direct handling). Therefore the individual lay-out of terminals will determine the exact impact on daily practices. Dry bulk terminals are not likely to invest in cranes on the short term.
  - Larger impacts on logistics are expected for non-container vessels and for vessels not being already a client of container terminals, because these cannot combine container loading and unloading with swapping.
  - Overall, additional time and potentially waiting times should be taken into account.

- Location and spatial requirements:
  - No new bunkering locations are needed. Existing container terminals can be used: The demand analyses and location requirement analyses show that the existing container terminals are well suited to handle the swapping of containers for H_2 vessels. In principle, no additional / new transhipment locations are required. For the concept of using H_2-containers, it is important that the options where H_2-containers can be swapped are as broad as possible. For this reason, it could be possible that other locations are added in the future, due to logistical or organisational reasons.
  - No extra space on container terminals is needed. Number of H_2-containers can be handled on existing infrastructure (now & future): The demand analysis show that the maximum number of H_2-containers expected in a port in 2040 (high scenario) and distributed over several terminals is not a reason for terminals to be expanded or for additional infrastructure to be required. The numbers can be handled with the existing resources and space.
    - No extra organisational adjustments are necessary. Current container terminal organisations are used with handling of dangerous goods.

- Demand
  - Based on the demand scenario and the total projected number of filled hydrogen containers needed, in 2030 an average of 11 – 148 filled hydrogen containers per day are needed in the Rotterdam area, depending on the total demand and the pressure of

  the hydrogen (300 – 500 bar); in Duisburg/Duisport area this number is 8 – 111 containers and in the RheinCargo area 4 – 56.
  - Based on 260 operating days per year, the projected number of vessels per day that demand hydrogen bunkering is for Rotterdam 2 – 31, for Duisport 2 – 23 and for RheinCargo 1 – 12 in 2030. The number of bunkering events could be higher in case vessels bunker multiple times during a round-trip.
  - This demand is expected to be affected by:
    - logistics strategies of ship owners and terminal organizations;
    - market developments in hydrogen supply (which can lead to different cost structures in different locations and varying logistics costs);
    - decisions based on financial grounds (actual costs of filled H_2-container in different locations).

- Safety & environmental demands:
  - Hydrogen is a dangerous good, safety requirements are therefore necessary on site and licenses are needed. However, many container terminals already are handling different dangerous goods including hydrogen. For these terminals the extra hydrogen containers will not have a substantial impact on their current procedures.
  - Environmental requirements only allow for temporary storage. In case of longer storage times additional measures might need to be taken by container terminal organizations.

- Investments needed:
  - There are no additional investment needed at (existing) container terminals which already handle dangerous goods.
  - Any additional costs related to container swapping are mainly linked to hydrogen price in which the cost for container handling/filling etc. will be incorporated.
  - Hydrogen producers are willing to invest in filling stations and container systems. Some optimization is possible regarding further scaling-up (higher frequency of transport to container terminals and/or filling speed at filling stations allowing growth.
  - Due to the small scale of container swapping, some investors are likely to wait for fixed tanks and hose bunkering options and some other investors might be reluctant to invest due the risks of stranded assets.

Bibliography

1 ADN, European agreement for transport of dangerous substances through inland waterways.

2 Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge- https://www.gesetze-im-internet.de/bimschg/

3 Breakthrough LNG Deployment in Inland Waterway Transport –

- Activity 5 Study into best locations for LNG bunkering stations &
- Activity 6.1 Comparison study on refilling of the LNG bunker station by tanker truck and by bunker barge, ENGIE LNG Solutions and Pitpoint, 2017.

4 Design Study, RH2INE project, final report, ZBT and Energy Engineers, 2021, June 2021

5 Directive 1999/92/EC of the European Parliament and of the Council of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres

6 Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissionshttps://eur-lex.europa.eu/legal-content/NL/TXT/?uri=celex%3A32010L0075

7 Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances (Seveso directive)

8 H_2-goederentrein, Haalbaarheidsstudie van goederentreinen rijdend op waterstof, Arcadis, 2020.

9 Interim report feasibility study RH2INE, ZBT, Duisburg, 12 February 2021

10 PGS15 Opslag van verpakte gevaarlijke stoffen (publicatiereeksgevaarlijkestoffen.nl)

11 PGS33-2 Aardgas afleverinstallaties van vloeibaar aardgas (LNG) voor vaartuigen en drijvende werktuigen (publicatiereeksgevaarlijkestoffen.nl)

12 PGS35 Waterstofinstallaties voor het afleveren van waterstof aan voertuigen en werktuigen (publicatiereeksgevaarlijkestoffen.nl)

13 Pre-study ZBT and Energy Engineers, 2021

14 stb-2018-293 besluit van 3 juli 2018, houdende regels over activiteiten in de fysieke leefomgeving (Besluit activiteiten leefomgeving)

15 SuAc 1.1c Hydrogen Demand Study, RH2INE program: Sub-Study 1a: Safety framework conditions, DNV, 2021

16 The National Hydrogen Strategy, Federal Ministry for Economic Affairs and Energy, BMWI, June 2020

17 Waterstof, Arcadis, juni 2020

Annex

Overview of interviewed parties:

- Air Liquide
- Air Products
- BCTN
- Covestro / NPRC
- Duisport
- ECT
- Future Proof Shipping
- HGK Shipping
- HTS Group
- Kramer Group
- Masslog GmbH
- NPRC
- Port of Rotterdam
- RheinCargo
- Shell
- Theo Pouw Groep