Challenges of integrating hydrogen in an operational port environment

Safety, Terminal Planning and Decision making aspects

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Challenges and opportunities of integrating hydrogen in an operational port environment
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Preface

This report was written as part of my graduation project which was the final step towards obtaining my MSc degree in Hydraulic Engineering offered by Delft University of Technology. While every part of my studies taught me a lot, this research is one of the most challenging and at the same time exciting tasks I have ever carried out. I knew since the first day I decided to leave Greece and chose to study in Delft, that my graduation project would be the most important 'ticket' for my working years to come. Taking into account the circumstances that this work was done, in the middle of a worldwide pandemic, I am proud that I finally completed it and even more proud to soon become a TU Delft alumni. Thus, I would like to express my gratitude to all the people that helped, advised, and even challenged me during this journey.

First of all, I would like to thank the chair of my graduation committee and advisor for many parts of this research, Professor Mark van Koningsveld. Despite his busy schedule, he was always eager to help me, and from the kick-off meeting of my thesis up until today he has constantly given me feedback that I highly appreciate. He was always a great motivation especially regarding coding and I owe him much of the programming skills I acquired all those months.

Secondly, my daily supervisor Dr. Poonam Taneja. She was the one that was there from the very beginning, since the end of my first year, to start brainstorming about an idea for a graduation project, bringing me in contact with many people and giving me opportunities that I otherwise would not have gotten. During my research she was always trying to keep an eye on me, warning me when she thought I was in trouble and praising me when she thought I did a good job. For all the practical information and scientific guidance she offered me, I am thankful.

Thirdly, Prof. Ad van Wijk for accepting to be a part of my graduation committee and actively being a member of it throughout the whole research. One could not be luckier to have a person with his knowledge and ideas on hydrogen, as a committee member for this research. With me coming from a civil engineering background and not being familiar with certain aspects of this study that I needed to take into account, his point of view helped me understand the importance of a new hydrogen economy as long as its challenges.

Last, but certainly not least, I would like to thank Daan Bos, my supervisor on behalf of Port Consultants Rotterdam. Our morning talks while drinking coffee at the office, the people I got to meet through him, and all his crucial help made this research much more interesting and fun. Many times I felt I had a supervisor and a friend at the same time. In addition, I would like to thank all the people of PCR (Pedja, Eric, Alejandra, etc) for our cooperation, along with every other person that helped me in this bumpy journey.

I could not forget the people that made me who I am, the people without which I would not be able to be in Delft, my parents. They were always there for me. When I was stressed or disappointed -and that happened often-, they were (and I hope that they will always be) a great encouragement. My brother with whom our relationship got so much better since I moved to the Netherlands, and all my friends both here and in Greece I really thank you all.

Serafeim Bachras, June 2022, Rotterdam

Abstract

Our planet is living in the era of climate change. In early November 2021, the 26th United Nations Climate Change Conference took place in Glasgow, leading to significant results -and some disappointments- that can decrease the impact of human-induced climate change on our planet. In order to meet the goals set during conferences like the one in Glasgow, our energy system is about to experience major changes in the years to come.

Hydrogen is expected to be a significant force in this transition. Hydrogen can be produced using technologies that do not emit CO_2 or other greenhouse gasses ("green H_2"). Hydrogen can be transported in big quantities and long distances unlike electricity and can play the role of a clean fuel. The emerging hydrogen economy, which will be accompanied by the gradual phase-out of fossil fuels, will significantly impact ports around the world. Ports can and should play a pivotal role in this "energy revolution". Apart from import and export services, ports often include industrial clusters, they provide servicing and refuelling to visiting vessels and connect major trade routes.

This study aims at understanding and providing insights on challenges that the above-explained transition will create in a port environment focusing on hydrogen. Firstly, a favourable policy environment for hydrogen projects in the ports and maritime sector is a key topic that this study will address. This is included as a conclusion in many reports and port conferences. Secondly, the questions related to terminal planning and area requirements of hydrogen terminals remain unanswered as large scale hydrogen projects do not exist yet -with many being under development-, and thus this research will try to shed light on area calculations of hydrogen terminals. Thirdly, and lastly, terminals operators, investors and policy makers will need to make decisions on the preferred hydrogen carrier and location for various hydrogen projects that will be developed in the near future. Therefore, a method of comparison of different alternatives is required, especially when terminals are planned next to existing liquid bulk terminals. The above lead to the main research question of this research:

"How can hydrogen (or a hydrogen carrier) be integrated as a new service in an operational port environment, and next to an existing liquid bulk terminal?"

To answer the main research question the scope of this study is limited, to the three challenges outlined above. An important aspect of hydrogen is that there are different ways to transport and store it. Besides pure hydrogen shipped and stored in liquid form (LH_2), ammonia (NH_3), green methanol and liquid organic hydrogen carriers (LOHCs) are some other alternatives. This study focuses on liquid hydrogen, ammonia and LOHC-DBT.

At first, focus is given on the three investigated carriers and their properties, to understand their advantages and disadvantages. Regarding safety regulations in a port environment, interviews with four different port authorities were scheduled, to understand what different ports in the Netherlands aim to do so as to develop hydrogen-specific rules. The findings showed a "chicken and egg problem" as ports are waiting for investments to finalize regulations, while investors on the other hand are expecting hydrogen regulations.

A method was also developed, which can provide a first estimate of the required area for a certain hydrogen demand. It is based on openTISim, a terminal investment simulation model developed by TU Delft. Furthermore, the user can provide a terminal boundary of given shape

and dimensions as input, and estimate the capacity of this given area, as well as a first visual representation of it. An important conclusion is the remarkably larger space requirement for a LOHC-DBT terminal, compared to the other two carriers. This is a sign however, that the model needs refinement and improvement for the DBT case. This impacts the cost of the lease of land. However, the impact on the cost in €/kg of H_2, appears to be minimal.

In addition, in cooperation with VOPAK and Port Consultants Rotterdam, a multi-criteria decision-making method was developed. The method focuses on investments in proximity to existing liquid bulk infrastructure and focus mainly on import terminal aspects and not to the entire hydrogen supply chain. Ten different criteria are specified and a general case with nine alternatives is analysed. The results show that an ammonia terminal in Vlissingen, a liquid hydrogen terminal in Rotterdam and a LOHC-DBT terminal in Eemshaven are among the most promising alternatives..

Finally, a case study of the VOPAK Terminal in Vlissingen is investigated. The area calculation model along with the decision-making method are used for this case. It concludes that an ammonia terminal is the preferred alternative and that the space next to the existing LPG terminal can accommodate a demand of about 720,000 tons of H_2 per year.

Recommendations for further research are provided based on the findings and the limitations of this study.

Nautical rules for vessels carrying hydrogen in bulk is not yet sufficiently regulated, and therefore quantitative risk assessment studies are necessary. The area calculations are very sensitive to the input values (tank inter distances, retrieval plant sizes etc), while a specific value for a large scale ammonia decomposition plant could not be determined. Considerable steps in certain technologies like ammonia decomposition are required, along with extensive research on tank sizes and inter distances. The model itself can be optimized as the method is very flexible. It allows the use of other sizes of tanks and/or H_2-retrieval plants, or even the use of two sizes simultaneously. Such changes can also decrease the chance of getting unrealistic layouts. The final recommendations include the investigation of the public perception of hydrogen related technologies as the social challenges of certain investments is a common question of many stakeholders, and the development of an updated multi-criteria analysis method, suitable also for greenfield projects.

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Acronym and Symbol list

AHP Analytical Hierarchy Process
CAPEX Capital Expenditure
CEN European Committee for Standardization
CH_3OH Methanol
CH_4 Methane
CO_2 Carbon Dioxide
DBT Dibenzyltoluene
BT Benzyltoluene
dwt Dead Weight Tonnage
EIGA European Industrial Gases Association
ELECTRE Elimination and Choice Translating Reality (translation from the French original)
GNA Gemeenschappelijke Nautische Autoriteit (Common Nautical Authority)
H_2 Hydrogen
ha hectares
IGC Code International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk
IMDG International Maritime Dangerous Goods
IMO International Maritime Association
ISO International Organization for Standardization
LH_2 Liquid Hydrogen
LNG Liquified Natural Gas
LOHC Liquid Organic Hydrogen Carrier
LPG Liquified Petroleum Gas
MCA Multi-Criteria Analysis
MCH MethylCycloHexane
Mtoe Mega tonnes of oil equivalent
N_2 Dinitrogen
NASA National Aeronautics and Space Administration
NH_3 Ammonia
NSP North Sea Port
openTISim Open source Terminal Investment Simulation
OPEX Operating Expenses
PCR Port Consultants Rotterdam
PoA Port of Amsterdam
PoR Port of Rotterdam
RWS Rijkswaterstaat
SIGTTO Society of International Gas Tanker & Terminal Operators
tn metric tonnes
TOPSIS Technique for Order Preference by Similarity to Ideal Solution
TRL Technology Readiness Level
WPM Weighted Product Model
WSM Weighted Sum Model
QRA Quantitative Risk Assessment

1 Introduction

It was back in 1859 when Edwin Drake completed the first drilled oil well near Titusville, Pennsylvania (Smil, 2017), an event considered as the beginning of the modern oil and gas era. Since then the oil and gas industry has become the major energy provider along with electricity. Unlike electricity, however, the use of fossil fuels in order to produce energy leads to carbon emissions and mainly emission of carbon dioxide (CO_2) which is the primary reason for global warming. It has become clear among scientists that robust differences in regional climate characteristics between today and global warming of 1.5^{o} Celsius can be expected (IPCC, 2018a), yet current warming rates are leading to a larger increase, as shown in Figure 1-1.

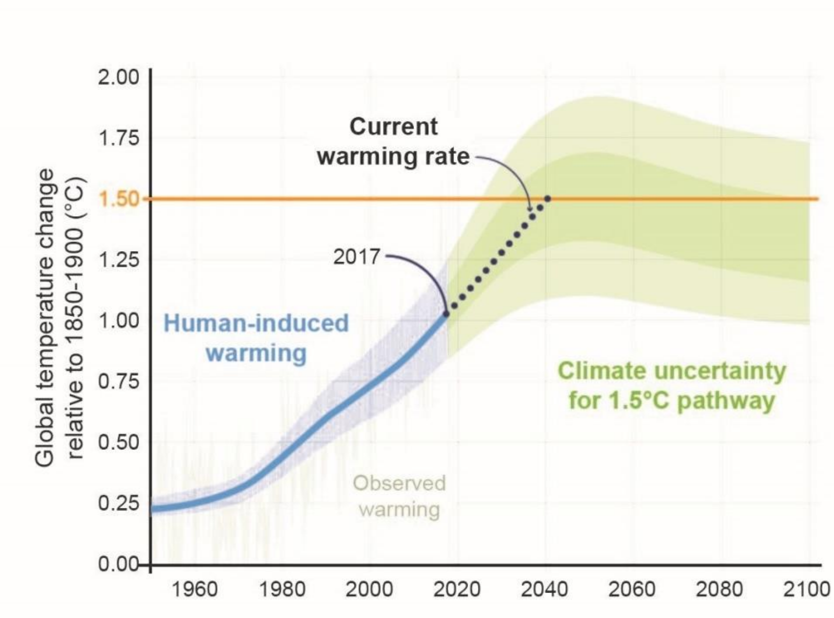

Figure 1-1: Human-induced global warming (IPCC, 2018b)

A major step towards a change of direction was the Paris Agreement signed in 2015 aiming at a carbon-free economy by 2050 (UNFCCC, 2017). The European Commission has since 2019 set a clear vision on how to achieve climate neutrality (European Commission, 2019), while in July 2021 the proposal of the 'Fit for 55' package, which aims at reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels, was announced (European Commission, 2021). However, it is more than clear that decarbonization is one of the most challenging goals of the energy sector (IEA, 2020b).

1.1 Background

Low carbon hydrogen seems to be one of the best alternatives for decarbonization and significant growth can be expected in hydrogen demand and supply. According to the Sustainable Development Scenario the supply of low-carbon hydrogen can be growing up to 215 Mtoe in 2040 (IEA, 2020c). Nowadays, almost all the hydrogen that is produced worldwide is so-called 'grey hydrogen' as it results in CO_2 emissions. As a consequence production of hydrogen is responsible for significant carbon dioxide emissions per year, in the order of 830 million tonnes (830 Mt CO_2/yr) (IEA, 2019). Hydrogen can become 'blue' when the CO_2 released during 'grey' hydrogen production is captured and stored. When hydrogen is produced with sustainable energy, it can be classified as ‘green hydrogen’ (TNO, 2019). A large part of the existing hydrogen demand is concentrated in port-industry clusters and in various cases (such as in Belgium and the Netherlands) these clusters already have a distribution network via pipelines (IEA, 2019). In that area, oil and gas refineries, storage facilities, and terminals play a very important role, and thus (parts of) already existing infrastructure could be exploited to store, produce and distribute hydrogen. The most efficient and safe way to transport and handle hydrogen is yet to be established, with ammonia (NH_3) being one of the most promising among the alternatives, due to its high volumetric energy density, and transportability (ISPT, 2017). Apart from ammonia, an easy way to transport hydrogen is using a liquid organic hydrogen carrier (LOHC), however NH_3 and LOHCs often cannot be used as products and a further step is needed to liberate hydrogen before consumption (IEA, 2019). Other promising alternatives may include the two ‘pure’ forms of it, pressurized hydrogen (H_2) and cryogenic hydrogen (LH_2) (Lanphen, 2019).

Around the world and also in the Netherlands more and more companies are investing in the hydrogen economy that is right now being created. In March 2021 Bill Gates along with various other business people announced a $22 million funding to an Israeli-based startup company called H2Pro. The funding is slated to take the company’s tech from laboratory prototyping to the factory floor through the production of commercial-scale electrolyzers (Taylor, 2021). Around the same time in the Netherlands Uniper and the Port of Rotterdam announced that they are starting a feasibility study for the construction of a 100MW green hydrogen plant by 2025 (Port of Rotterdam Authority, 2021), while a consortium of Gasunie, Groningen Seaports, and Shell Nederland has launched the ambitious NortH2 green hydrogen project aiming to a production of 800.000 tonnes of hydrogen per year by 2040 (Gasunie, 2021b) and Transhydrogen Alliance (a consortium of international companies) aims at importing 500,000 tonnes of green hydrogen in the long term, via the PoR in Europe, using ammonia as a hydrogen carrier (Offshore Energy, 2021). The project is expected to be operational by 2024. The above are just some examples of the numerous projects that indicate that hydrogen is soon to play a decisive role in the energy transition taking place.

1.2 Research gap and objective

A large part of the port industry right now especially in Northern Europe is energy-related. From oil to LNG and LPG, to dry bulk like coal. Figure 1-2 depicts that for the Port of Rotterdam, energy related cargo (assuming that coal is divided into thermal and metallurgical coal about 75-25% (IEA, 2020a), and that other liquid bulk is not considered energy related) accounted for more than 40% of the total throughput for all the three shown years. As part of the incoming cargo which is mainly imported cargo, energy related cargo accounts for about 50% of the imports. Similar to Rotterdam, energy-related cargo accounts for a big part of the cargo throughput in other ports in the region like North Sea Port (North Sea Port, 2019).

TOTAL THROUGHPUT BY COMMODITY

	2019	2018	2017
Iron ore and scrap	30.0	30.1	31.2
Coal	22.4	26.4	25.8
Agribulk	9.8	9.9	11.1
Other dry bulk	12.2	11.3	12.1
Subtotal dry bulk	**74.5**	**77.6**	**80.2**
Crude oil	104.2	100.3	104.2
Mineral oil products	68.2	77.7	79.2
LNG	7.1	5.2	2.0
Other liquid bulk	31.7	28.6	28.9
Subtotal liquid bulk	**211.2**	**211.8**	**214.3**
Total bulk goods	**285.7**	**289.5**	**294.5**
Containers	**152.9**	**149.1**	**142.6**
Roll-on/Roll-off	24.3	24.1	23.8
Other general cargo	6.5	6.4	6.5
Total breakbulk	**30.8**	**30.4**	**30.3**
Total throughput	**469.4**	**469.0**	**467.4**

Unit: Gross weight x 1 million metric tons   Source: Port of Rotterdam

INCOMING AND OUTGOING BY COMMODITY 2019

	Incoming	Outgoing	Total
Iron ore and scrap	27.6	2.4	30.0
Coal	21.7	0.8	22.4
Agribulk	8.9	0.9	9.8
Other dry bulk	10.1	2.1	12.2
Subtotal dry bulk	**68.3**	**6.2**	**74.5**
Crude oil	103.3	0.9	104.2
Mineral oil products	35.7	32.5	68.2
LNG	6.5	0.6	7.1
Other liquid bulk	19.5	12.2	31.7
Subtotal liquid bulk	**165.0**	**46.2**	**211.2**
Total bulk goods	**233.3**	**52.4**	**285.7**
Containers	**78.0**	**74.9**	**152.9**
Roll-on/Roll-off	10.3	14.0	24.3
Other general cargo	4.2	2.3	6.5
Total breakbulk	**14.5**	**16.3**	**30.8**
Total throughput	**325.8**	**143.6**	**469.4**

Unit: Gross weight x 1 million metric tons   Source: Port of Rotterdam

Figure 1-2: Cargo Throughput PoR by sector (Port of Rotterdam, 2019)

Thus, dealing with the challenges of the energy transition in the port environment is crucial for all the stakeholders involved in the port industry, as the energy sector and especially the fuel market can be expected to radically transform in the coming year. This research will try to address some of the gaps that exist nowadays, regarding hydrogen in a port environment.

Regulations are one of the limiting factors in the development of a clean hydrogen economy (IRENA, 2019). A possible harmonization of regulations between different ports and areas could boost investments, as common international standards for transporting and storing large volumes of hydrogen would benefit the hydrogen supply chain trade (IEA, 2019) considerably, making large-scale international hydrogen-related projects easier and more attractive to investors (Andreasson et al., 2021). The lessons learned from small-scale hydrogen projects as well as the world's first liquefied hydrogen receiving terminal -Hy touch Kobe, Japan- whose completion was announced in December 2020 (Kawasaki, 2020) can prove to be highly influential. The first liquefied hydrogen cargo from Australia to Japan is expected to be shipped during 2021.

At the same time, large-scale hydrogen terminals are yet to be constructed. Is it certain, that in the next years -when hydrogen supply chains like the one between Australia and Japan will start emerging around the globe- hydrogen import and export terminals will be present in many parts of the world. In March 2021 for example, the Port of Rotterdam signed a memorandum of understanding with the Chilean government aiming to import green hydrogen from Chile (Port of Rotterdam, 2021). However, the exact layout and required area of a hydrogen terminal is not certain and naturally depends on the hydrogen carrier[1]. Given that most hydrogen carriers have a smaller volumetric energy density of fuels we use at the

[1] A hydrogen carrier is a substance that consists of hydrogen and other molecules and can be used as a medium to transport, handle and store hydrogen in an easier way. Hydrogen carriers have to be de-hydrogenated via cracking or other similar chemical reactions, before utilizing their hydrogen.

moment, the area that will be required for the storage of hydrogen may prove a critical parameter of an investment, while processes like hydrogen production, gasification, hydrogenation, etc. also require additional space. A recent report on the implications of the energy transition to the area requirements in the Port of Rotterdam, showed that a significant amount of extra land will be required, for almost every one of the investigated scenarios (Smart Port, 2021).

A study by Alvita, (2020) which focused on the calculation of the area required for a container terminal, used a simple, straightforward method where the area is calculated based on the number of container blocks that a model has produced and the type of the container terminal. This method was able to also calculate the capacity that a given terminal boundary can accommodate. A method on how to calculate the area required for a hydrogen terminal and how to use terminal space in an optimal way is needed.

Simultaneously, in the pursuit of this new energy market, the hydrogen market, major terminal operators will need to decide on where the terminals will be located, and which hydrogen carrier is the best alternative for them. Port location studies have been studied extensively in the past. Ares Moreno, (2018) and Oosterwegel, (2018) are some of the examples where different methods and criteria were used to determine the preferred port location. Ares Moreno, (2018) developed a method for a "green port". Oosterwegel, (2018) conducted a study, in sustainable port development, international guidelines on site selection and expert consultation, that led to a framework for a proper site selection. When focusing on the oil and gas industry, many examples of cases and methods exist. Bagočius et al., (2014) investigated the best location of an LNG terminal using various methods. Similar methods will be applied and are already being used for the even more complicated decisions required for hydrogen terminals. Especially taking into account the great amount of infrastructure that the oil and gas industry already operates, one can understand that such a decision is both important and multivariate. Existing infrastructure will not be needed in some years, while getting to a carbon-neutral energy system, but could be transformed to accommodate other fuels like hydrogen and ammonia. Several companies and reports have investigated such options (Black & Veatch, 2020; Kolff, 2021). PCR's communication with a major terminal operator made clear that such decisions and with no existing hydrogen supply chains developed, are a significant question for the industry.

> Optimal use of space as well the total area required is a topic of interest for other industries too. Office real estate researchers have been studying office space demand for years (Miller, 2012). EIB, (2011) calculated office space demand for the city of Utrecht while Cheng, (2022) proposed a formula that focuses on office demand forecasting at a corporate level. In Cheng's study variables like the desk occupancy rate (similar to berth occupancy in a port application, that affects the number of storage tanks) and the employment structure (similar to the strategy of a liquid bulk terminal) are taken into account.

Research Objective

Studying the supply chain of different hydrogen carriers, from hydrogen production to transport and storage, to the end-use, is a topic that many researchers have studied like the study of Abrahamse, 2021 which was finalized some months ago. Due to the fact that hydrogen is not a commodity and large-scale terminals do not exist, the current study is focusing on the design of hydrogen import terminals and safety regulations regarding hydrogen in a port environment. In the Figure below an example of the hydrogen supply chain is depicted, and the scope of this study is highlighted. It should be noted, that certain parts of the supply chain that are extremely important like the hinterland transport from the import terminal to the end-user, or large scale storage in salt caverns, are not shown for simplicity, as the aim of the figure is to highlight the part of the supply chain which is part of the Scope of this study. Part 7 of the supply chain, Gasification/De-hydrogenation may or may not be in the port itself and thus the possibility that this happens in the port is included in the scope of this research, while the case where de-hydrogenation happens at the end-user is considered out of the scope (centralized versus de-centralized case).

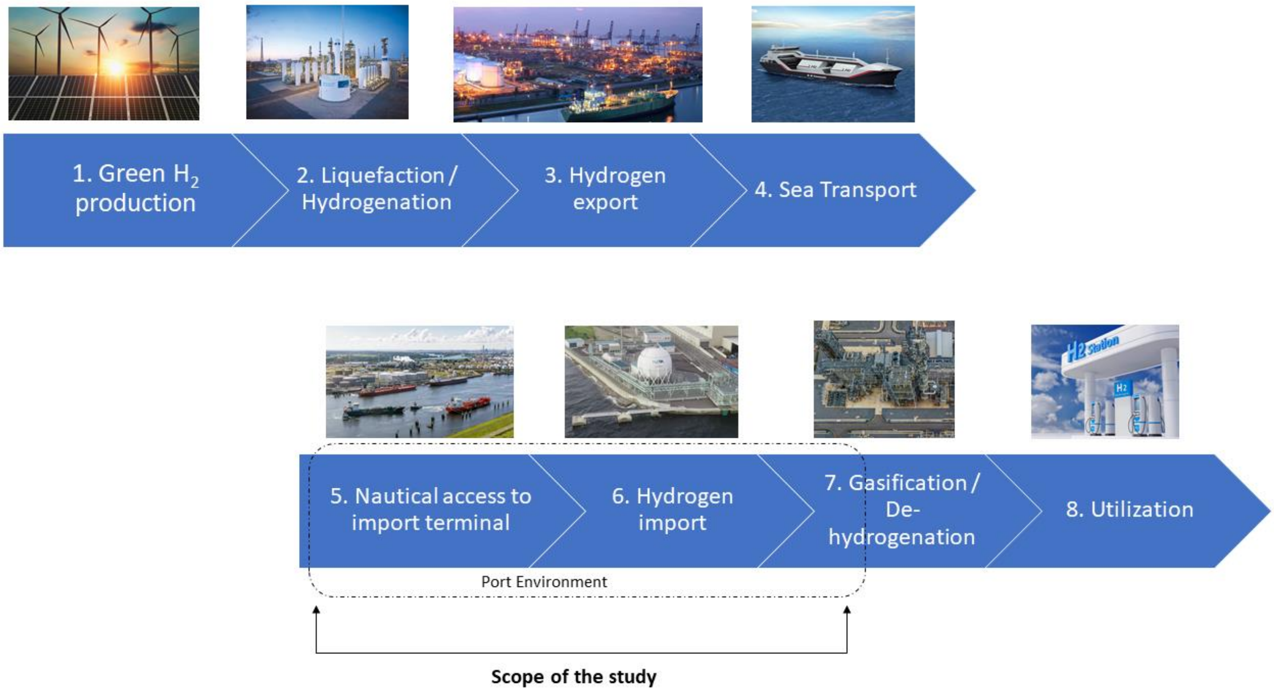

Figure 1-3: Hydrogen supply chain and scope of the current research (author's illustration)

The main objective of this research is to address certain challenges of adding hydrogen –using cryogenic hydrogen, ammonia, or a LOHC as a carrier– next to an existing liquid bulk terminal in the Netherlands, and develop methods and guidelines so as to tackle those challenges. This will be conducted focusing on the three following pillars:

1) Safety regulations that apply to the transport of those products in a port environment and the readiness level of ports to accommodate hydrogen cargo
2) Space requirements of a new hydrogen import terminal and
3) Decision making aspects related to the terminal location and hydrogen carrier

Existing regulations regarding other liquid bulk cargo safety aspects, both nautical and storage, can act as a starting point when similarities between the hydrogen carrier and an existing cargo are significant as well as the physical and chemical properties of the hydrogen carriers compared to existing cargoes.

At the same time, given the fact that large-scale hydrogen terminals do not exist at present, the space requirements are not yet fully defined. The above applies to liquid hydrogen and LOHCs, as ammonia is a commodity and thus ammonia terminals exist throughout the globe, however its differences in terms of area requirements with the other two carriers are unclear. As a result, part of this study will be dedicated to the calculation of the required terminal area.

The above will help in developing a method to compare different terminal alternatives that include both the port locations and the carrier. A comparison between three port locations and terminals owned by VOPAK will be used as an example. Royal VOPAK N.V. is a Dutch multinational company that stores and handles various oil, chemicals, edible oils, and natural gas-related products and is a partner in this study. The three VOPAK locations that will be considered are in Vlissingen, Rotterdam, and Eemshaven. For the Rotterdam case, further elaboration will be done later on, regarding the exact location to be compared per carrier. Using this method, and the work related to safety requirements and area calculations one of the three port locations will be used as a case study. Any data and information obtained from VOPAK will be treated as confidential; VOPAK will also indicate which part of the thesis results is to be kept confidential.

1.3 Research Question

Based on the introduction and the problem statement as explained above the research question and sub-questions can be stated:

"How can hydrogen (or a hydrogen carrier) be integrated as a new service in an operational port environment, and next to an existing liquid bulk terminal?"

The research will address various sub-questions, in order to answer the main research question, which are listed below:

A. What are the properties of the studied hydrogen carriers, what is the state of the art technology regarding those carriers, and what advantages and disadvantages does each one have?
B. How do different stakeholders approach nautical safety of hydrogen (or hydrogen carriers) in a port environment, and what are the limitations (if any) in the possibility of a hydrogen vessel sailing through a lock?
C. How can the required terminal area for a certain carrier be calculated, taking into account safety and technical aspects, for a given throughput or the other way around? (calculate the throughput that a certain area can accommodate). What will a conceptual design of such a terminal look like?
D. Using a method of comparison (to be defined or developed as part of this research), determine which of the investigated alternatives would be the most attractive to develop and for which type of activity. Which indicators can be used in order to compare the alternatives and how can they be quantified?
E. Based on the method of comparison, and using the model developed, what would the preferred carrier be for the investigated case study and how will a conceptual design of the terminal look like?

1.4 Research Method

To conduct the above research, a literature review will be necessary. First, a review of hydrogen carriers in terms of properties, transport and storage, and safety will be executed. Information on conversion plants will also be reviewed. The H_2 logistics chain will be briefly described, along with the differences of each carrier, and the latest technological developments. This study is focusing on the port environment, which includes the nautical access to a terminal, the import terminal itself and possible conversion facilities that will be constructed in the port and thus an overview of some advantages and disadvantages of the three carriers will be presented. A brief summary of existing guidelines and standards will also be presented.

In order to investigate the framework and regulations related to nautical safety interviews with port authorities and other competent authorities will be scheduled. Four port authorities in the Netherlands will be interviewed: North Sea Port, Port of Rotterdam, Port of Amsterdam and Groningen Seaports. Port of Amsterdam could also be of interest due to the existence of the locks in Ijmuiden. Thus, questions regarding regulations that apply to the locks as of today during the interview with the Port of Amsterdam, and their idea on how they see the possibility of having a hydrogen vessel in the lock will be asked. A similar interview can be scheduled with RWS given the existence of the locks in Terneuzen, and the Panama Canal Authority taking into account the Panama Canal's vital role in large scale supply chains. The results of this 'stakeholder analysis' will be summarized to derive useful conclusions regarding nautical safety of hydrogen in a port environment and the possibility of hydrogen vessels passing through lock chambers.

Part of the research will focus on the development of a method in order to calculate the required terminal area for each carrier, given a throughput. The opposite procedure, calculating the throughput that a specific area is able to accommodate, will be also possible for the user to conduct. The above will be done using the existing openTISim software as a basis. The method will give the user the possibility to include a conversion plant to the terminal, for the dehydrogenation of a LOHC for example. Based on the literature review conducted before, the model input will be determined. The terminal area development over time will be produced as output of the model, along with the layout of the terminal based on certain design rules. In addition, the method will have the option to use a given terminal as input and calculate the demand that this given terminal boundary can handle. This process will follow a similar way of thinking to the method developed by Alvita in 2020 for container terminals.

Working on the above explained actions (carriers advantages and disadvantages, nautical safety, terminal design tool, etc.) as a basis, different aspects that affect a decision related to a hydrogen import terminal will be taken into account in order to gain insights on how to make such a decision. A common way to do so is a Multi-Criteria Decision Making (MCDM) approach, where different alternatives are compared in a decision making problem. In this research, the alternatives are the different carriers (LH_2, NH_3, and LOHC) per location. The exact criteria and their corresponding weights have to be specified later on in the corresponding chapter. Examples of decision criteria can be: the similarities of the new service to the existing terminal cargoes, the ease of compliance with existing (and possibly new) regulations, the Technology Readiness Level (TRL) of the transport/storage of a carrier, the

There are three main steps in utilizing any decision-making technique involving numerical analysis of alternatives (Triantaphyllou, 2000):

1. Determine the relevant criteria and alternatives.
2. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
3. Process the numerical values to determine a ranking of each alternative.

One of the most commonly used models is the weighted sum model (WSM), which compares *m* alternatives using *n* criteria. WSM is just an example of a way to quantify the scoring and comparison of different alternatives.

required area and the availability of land next to the existing terminal or typical port location criteria like the connection to the hinterland.

A method will be developed for the comparison of the different alternatives. After concluding the exact method, criteria and weights, the method will be used to compare some real-life alternatives. The three terminals to be examined are owned partially or as a whole by VOPAK:

1. VOPAK Terminal Vlissingen – North Sea Port
2. VOPAK Terminal Eemshaven – Groningen Seaports
3. Gate Terminal and Botlek Terminal – Port of Rotterdam

Each of the above terminals provides different services. For example, VOPAK Terminal Vlissingen is an LPG terminal, while VOPAK Terminal Eemshaven is a crude oil and petroleum products terminal. Using the aforementioned method the highest scoring alternative(s) will be decided.

Based on all the output of the study and using the design tool and the decision-making method, a detailed analysis of a case study will be conducted, in order to validate the methods in a realistic scenario, check possible limitations and of course provide recommendations on how to develop a hydrogen terminal for this specific case. The VOPAK Terminal in Vlissingen will be the investigated case study.

1.5 Report Outline

This section is providing an outline of every chapter of this study. To begin with, in the following Chapter, (Chapter 2 of this study) a summary of the three investigated carriers is presented. Their properties, including properties related to safety along with the state of the art in storage, transport and conversion technologies are presented. A table with advantages and disadvantages is produced and shown at the end of the Chapter summarizing the above.

In Chapter 3 a stakeholder analysis is conducted aimed at providing insights on nautical safety aspects of hydrogen-related vessels. Given the fact that LOHC-DBT vessels are expected to be conventional tankers without any extra limitations and that ammonia transport already happens worldwide, this part is focusing on vessels carrying liquid hydrogen in bulk. Interviews with port or other competent authorities are the foundation of the stakeholder analysis. A brief investigation of safety aspects related to lock transits is conducted as well, again via interviewing experts and involved stakeholders.

Chapter 4 is focusing on the development of a design tool on hydrogen terminals on the basis of the existing openTISim package. The area of the hydrogen terminal for each option of hydrogen carrier will be calculated and a conceptual design visualization will be produced for a given terminal boundary.

In Chapter 5 a multi-criteria analysis will be conducted, based on a method developed as part of this study. The method will help in the decision-making problems of hydrogen import terminals. The alternatives will be comprised of combinations of locations and hydrogen carriers. Three port locations in the Netherlands will be investigated and compared using this method so as to conclude which options are the most preferable.

Based on the methods developed in Chapters 4 and 5, the VOPAK Terminal in Vlissingen (North Sea Port) will be used as a case study (Chapter 6). The aim is to first define the preferred carrier based on the Multi-Criteria Analysis developed in Chapter 5. Using openTISim the demand that the area of the terminal can handle will be approximated.

In Chapter 7 the results are discussed along with some recommendations for further study, while the last Chapter of the study, Chapter 8, includes conclusions that all the above led to, answering the sub-questions and the main research question.

2 Literature Review

In order to understand the properties and characteristics of hydrogen carriers, a literature review is first conducted. For each one of the three carriers, four different aspects are investigated: properties, transport and storage, safety and H_2 retrieval. The above are vital elements when designing a hydrogen import terminal and thus crucial for this study. After the review of the three carriers, a summary of their pros and cons is presented. At the end of this chapter, an overview of existing safety regulations related to hydrogen is given. The Chapter's goal is to answer sub-question A.

2.1 Hydrogen Carriers

Hydrogen alongside widespread electrification potentially has a valuable role in replacing natural gas (e.g. in industrial processes) and liquid fuels (e.g. in heavy transport) (Jackson et al., 2020). The two 'pure' forms of hydrogen (compressed H_2 and LH_2) have the advantage that no conversion is required, which decreases the cost and increases the efficiency of the technology. However, when talking about compressed hydrogen a major drawback is its low volumetric capacity while the safety aspect of storing hydrogen at a high pressure (700 bar) has to be taken into account (Gkanas, 2018). Generally, safety standards exist, and thus storing hydrogen at high pressure in tanks in the open air is considered safe. Out of these two forms of hydrogen only liquid hydrogen -LH_2- will be investigated in this research.

Hydrogen instead of being a molecule on its own can be attached to a lot of different substances, such as methanol, ammonia, ethanol, dibenzyltoluene, methylcyclohexane and sodium borohydride (Lanphen, 2019). Ammonia has the advantage of not needing CO_2 to be produced and that its boiling temperature is moderate (Hydrogen Import Coalition, 2020). Apart from that, there is a well-established ammonia supply chain. A disadvantage of ammonia though, is the reconversion of ammonia into hydrogen. The technology is mature enough, but large-scale decomposition plants have not been constructed yet, as there was no need to do so, until today. The molecule to represent the broad group of LOHCs is Dibenzyltoluene[2] (DBT). This decision was made after comparing the three promising LOHCs: DBT, MCH and methanol. The comparison can be found in Appendix A – LOHCs comparison. Similar to most LOHCs the hydrogenation and dehydrogenation steps are still uncertain and challenging (Hydrogen Import Coalition, 2020).

As a result, three hydrogen carriers (LH2, NH_3 and DBT) will be the ones to be considered the most interesting. Some basic properties of each of the three carriers can be found in Table 2-1 below.

[2] Dibenzyltoluene (DBT) has very similar properties with Benzyltoluene (BT) and therefore in some cases existing studies and information regarding BT will be used later on in this study.

Property	*Liquid Hydrogen*	*Ammonia*	*DBT*	*Unit*
Chemical Formula	H_2	NH_3	$C_{21}H_{32}$[3]	[-]
H_2 %wt	100	17.6	6.23	[%wt]
Boiling Temperature (1 bar)	-253	-33.4	390	[°C]
Liquid Density (1 bar)	70.5	682	921	[kg/m^3]
Hydrogen density (1 bar)	70.5	120	57	[kg H_2/m^3]
Energy density	10011	15345	8094	[MJ/m^3]
Flammability limits of gaseous H_2 and NH_3 in air	4 - 74	14.8 – 33.5	Hardly flammable	[%]
Minimum ignition energy	0.02	680	High	[mJ]
Buoyancy factor (for gaseous H_2 and NH_3)	1.202	0.562	-	[kg/m^3]

Table 2-1: Properties of the three investigated hydrogen carriers

2.1.1 Liquid Hydrogen / LH_2

Between the two pure forms of hydrogen, liquid hydrogen is of more interest. This is because storing and transporting large amounts of compressed hydrogen does not seem to be a viable solution. When hydrogen is converted into its liquid phase, the energy density increases dramatically, about 850 times (European Industrial Gases Association, 2002). Liquid hydrogen can be transported and stored using cryogenic tanks, displaying a lot of similarities with the transport and storage of LNG, which has proven a cost-efficient and safe solution when handling gas (Deltalinqs, 2019; IRENA, 2019). After hydrogen is produced, it has to be liquified, transported, stored and gasified again in order to be used (Wijayanta et al., 2019). In Figure 2-1 a schematic route of an LH_2 supply chain is shown. The greatest advantage of a pure form of hydrogen is the fact that no de-hydrogenation and purification is needed. Historically, the Euro – Quebec project in the 90s was one of the first projects aiming to create a liquid hydrogen supply chain, investigating the feasibility of shipping green hydrogen from Canada to Germany (Giacomazzi & Gretz, 1993).

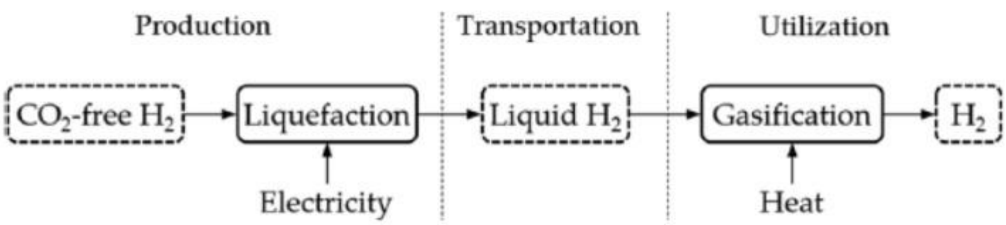

Figure 2-1: Schematic route of an LH_2 supply chain (Wijayanta et al., 2019)

<u>Properties</u>

Liquid hydrogen is colourless and odourless, and its density is approximately one-fourteenth of that of water. Liquefaction of hydrogen requires an extremely low temperature

[3] It must be noted that the chemical formulas and certain properties of LOHCs are obviously different when they are hydrogenated and when they are de-hydrogenated. The ones of the hydrogenated LOHC are used in the tables, unless else specified.

of about -253 °C (about 91 °C lower than LNG) while its density is about 70.5 kg/m^3, significantly lower than that of ammonia. In Table 2-1 more properties of hydrogen can be found, while Figure 2-2 below, shows the phase diagram of hydrogen, where one can see the temperature required to liquefy hydrogen under ambient pressure.

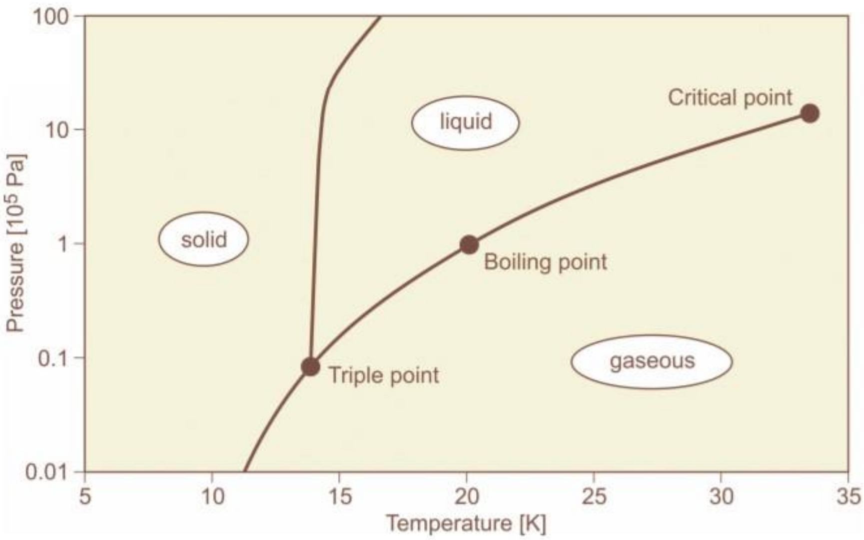

Figure 2-2: Hydrogen Phase Diagram

A comparison between LNG and LH_2 based on their properties can be seen in Table 2-2. The energy required to liquify H_2 and natural gas is provided in kWh/kg gas. It should be noted however, that 1 kg of H_2 and 1 kg of natural gas have different energy content. In addition, the values are based on technical reports and measurements, and are thus different than the minimum required theoretical values. The values are based on Department of Energy, (2019; Zhang et al., (2020).

Property	*Liquid Hydrogen*	*LNG*	*Unit*
Chemical Formula	H_2	CH_4	[-]
H_2 %wt	100	24	[%wt]
Boiling Temperature (1 bar)	-253	-161.5	[°C]
Liquid Density (1 bar)	70.5	430 – 470	[kg/m^3]
Energy density	10011	22500	[MJ/m^3]
Flammability limits in air	4 - 74	4 – 15	[%]
Minimum ignition energy	0.02	0.28	[mJ]
Energy required to liquify	12	0.4	[kWh/kg]

Table 2-2: LNG and LH_2 comparison

Transport and Storage

After hydrogen gas is produced -either brown, blue or green- it will need to be transported to the area where the demand is high. As explained before the production and demand areas will almost certainly differ. In case of small distances (for example green hydrogen production using wind energy from the North Sea in the Port of Rotterdam) the produced hydrogen gas can be instantly put into a hydrogen pipeline network and transported around the Netherlands and northern Germany. However, the local demand will certainly be higher than local production and thus large distances will need to be covered.

In 2015 Kawasaki developed the conceptual designs of a sea-going LH_2 tanker with a capacity of 160,000 m^3 and a small LH_2 vessel, carrying 2,500 m^3. The latter was actually built and is already operational in the Hydrogen Energy Supply Chain (HESC). The large ship that was developed is equipped with 4 spherical tanks (MOS-type) with a capacity of 40,000 m^3 each (Kamiya et al., 2015). The tanker design was based on existing LNG standards due to the similarities between LNG and LH_2 (Wijayanta et al., 2019). Like LNG, storing LH_2 leads to Boil-off Gas (BOG). BOG is the gas that is evaporated in the storage tank as perfect insulation against warming is not possible. The very low storage temperature can lead to a significant boil-off rate depending on the amount of insulation. BOG is inevitable and must be managed effectively, by using it as fuel, re-liquefying it or burning it, to avoid cargo tank pressure issues (Lee et al., 2019). In the case of an LH_2 import terminal connected to an H_2 grid, BOG can be compressed and then supplied to the grid.

When it comes to the storage of LH_2 things get a little less complicated. This is because NASA is storing LH_2 for decades now so the technology is more or less developed. A scale-up of existing tanks can be expected in the next decades leading to tanks with a capacity of 50,000 m^3 (NCE Maritime CleanTech, 2019). In December 2020 Kawasaki announced the completion of the basic design of an 11,200 m^3 spherical liquified hydrogen storage tank (Kawasaki, 2020). In the figure below, the new LH_2 tank at the port of Kobe (2,250 m^3) is not included.

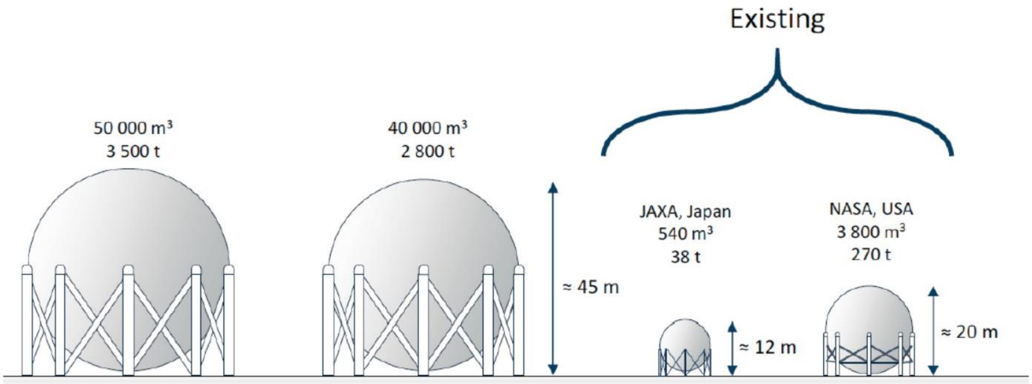

Figure 2-3: LH_2 storage (NCE Maritime CleanTech, 2019)

Storage is possibly the best regulated part of the liquid hydrogen value chain as the European Industrial Gases Association (EIGA), ISO and CEN have all published on the use of cryogenic tanks for liquid hydrogen storage. For example, EIGA document 06/19 gives specific guidance on the layout and locations of installations of LH_2 terminals. However, most existing regulations and standards refer to small scale storage tanks. Further elaboration on the layout of an LH_2 import terminal will be done in Chapter 4.

Safety

As can be seen from Table 2-1 gaseous hydrogen is highly flammable. Its lower flammability limit (LFL) is around 4% and the upper-flammability limit (UFL) is around 74% in ambient conditions. Compared to LNG, looking at Table 2-2, one can see that LH_2 is more flammable while less energy is required to ignite. Despite the high flammability, however, in open areas like a hydrogen import terminal the risk is relatively low as in case of a leakage hydrogen rises and disperses before it could ignite. In the case of a crack on a LH_2 tank, liquid hydrogen will evaporate while freezing oxygen and nitrogen of the air. On the other hand, in an enclosed space hydrogen gas may get trapped, leading to higher overpressures and thus higher risk (Kovač et al., 2021). According to EIGA "all hydrogen storage installations shall be situated outdoors" (EIGA, 2019).

A detailed analysis of the factors and potential risks of liquid hydrogen applications is out of the scope of this study. However, even though experimental measurements provide valuable insight, they are limited, expensive and even impossible, particularly for more realistic large scale accidents (Abohamzeh et al., 2021). Thus, computational fluid dynamics (CFD) techniques are the best tool to understand the risks related to hydrogen handling and applications. The literature review made clear that there is a scarcity of data for cryogenic systems compared to compressed hydrogen systems (Panda & Hecht, 2016). In an open environment like in the case of a liquid hydrogen terminal that was modelled by Giannissi & Venetsanos, it was proven that CFD models can properly depict experimental data and that different factors like the wind velocity and variability can prove very important in the dispersion in case of a leakage. These kinds of studies are the basis for the global regulations of large scale storage that can be expected to happen in the following years.

LH_2 re-gasification

After storing hydrogen in liquid form, it is most probably going to be re-gasified and fed into a hydrogen grid. Facilities that carry out this process are not constructed on a large scale at the time this research is conducted. However, from a fundamental point of view, LH_2 re-gasification is similar to LNG re-gasification and therefore, the methods to re-gasify LH_2 can be inspired from those known for LNG (Laouir, 2019). Kolff, in 2021 examined the possibility of retrofitting an LNG facility to a facility suitable to process hydrogen. This included an in depth analysis on storage and re-gasification of LH_2. According to Kolff, multiple re-gasification technologies are available for LNG. One of the cheapest and most widely used ones is the Open Rack Vaporizer (ORV), which uses seawater as a heat source, which is, of course, abundant in a port environment and easily obtained. In addition, increasing or decreasing the number of panels (and hence the capacity of the facility) is easy, allowing a flexible design and vaporizers with large capacities up to 300 ton/hr (Egashira, 2013). I n Kolff's study a SuperORV re-gasification plant is assumed, similar to existing LNG ones.

Regarding the footprint of such an LNG vaporizer, a rectangle of approximately 17 x 11 m, can have a capacity of approximately 150 ton/hr (Hisada & Sekiguchi, 2004). A better indication of the footprint related to the vaporizer's capacity can be obtained by comparing different existing LNG vaporizer's, for example at the Gate Terminal in the Port of Rotterdam. It is clear, that this facility for an LH_2 import terminal is going to be very similar to the LNG ones and its space requirement is not very significant. Further elaboration on the footprint can be found in Section 4.5.

2.1.2 Ammonia / NH_3

Ammonia (NH_3) is one of the most commonly produced chemicals worldwide. In 2017 the ammonia production worldwide was approximately 180 million tons, with a steady growth every year of about 1.5% to be expected. Out of this production, more than 80% of ammonia is consumed in agriculture by the fertilizer industry (Kaczmarek et al., 2014). At the moment ammonia is used mainly in its pure form without extracting the hydrogen out of it.

Apart from being used in the fertilizing industry though, ammonia is highly valued as a promising option for hydrogen storage. It has a relatively high energy density of 17.8 wt%

while being able to fulfil the demand to store energy both in time and in space (Aziz et al., 2020). The way a supply chain of ammonia could work can be seen in Figure 2-4. This graph includes ammonia production from fossil fuels. To produce ammonia, hydrogen is required. Like hydrogen, ammonia can be produced without emissions, leading to "green ammonia". This implies that both the hydrogen production and nitrogen extraction from the air should be done using renewable energy. Ammonia production from H_2 and N_2 is an exothermic reaction that does not produce greenhouse gases. After production ammonia can be easily transported and stored. Direct utilization of ammonia is of course possible, or ammonia should be decomposed again and utilize the produced hydrogen.

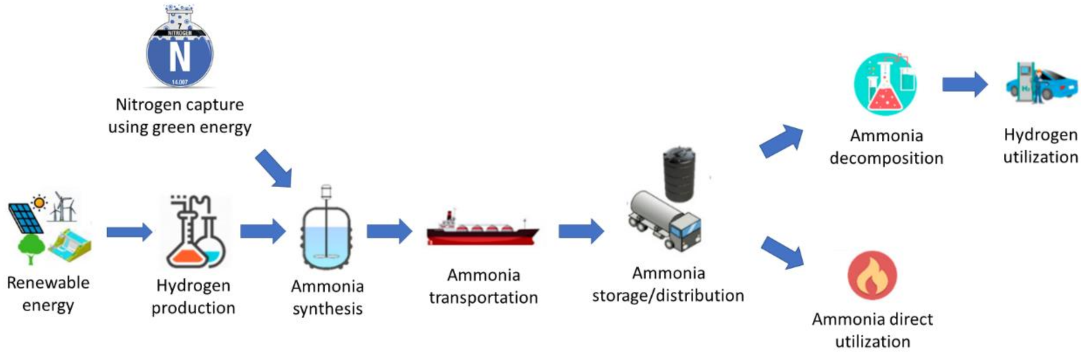

Figure 2-4: Ammonia supply chain (modified from Aziz et al., 2020)

Ammonia can be potentially used as a fuel for internal combustion engines, as a direct way to utilize it in another sector other than the fertilizer industry. However, the very high ignition energy that ammonia requires makes the use of another fuel almost necessary for ignition (Kobayashi et al., 2019). Ammonia as a fuel is particularly interesting for the maritime industry, as it is a clean fuel in the industry's path to decarbonization. The only concern is the emissions of NO_x when directly utilizing NH_3. A lot of studies worldwide aim at investigating the supply chain of green ammonia ship-to-ship bunkering. When comparing NH_3 with LH_2 and CH_4 as maritime fuels and taking into account the fact that CH_4 is not a clean fuel, ammonia seems to be the best alternative (Kwon, 2019).

Recently a lot of major companies including Maersk, Kepper Offshore & Marine decided to conduct a feasibility study at the Port of Singapore, the largest bunkering port in the world (Jiang, 2021), while DSME and Man got approval to start building an ammonia-fueled container vessel (Lloyd's Register, 2020).

Properties

Ammonia is a gas under atmospheric conditions. It is a colorless gas with a characteristic pungent odor that is lighter than air. In addition, ammonia has a boiling point of approximately negative thirty three degrees (-33,3^{o}C), is partially soluble in water and is considered caustic and hazardous (Fecke et al., 2016). In Figure 2-5 the phase diagram of ammonia can be seen. An overview of the properties of ammonia can be seen in Table 2-1 above, seeing that about 120 kg of hydrogen are contained in every cubic meter of ammonia. Due to its high volumetric energy density, transportability and low cost of N_2 sourcing, ammonia has a great prospect either as a fuel itself or as a hydrogen carrier. However, a significant barrier for ammonia is its toxicity (further elaborated later under 'Safety').

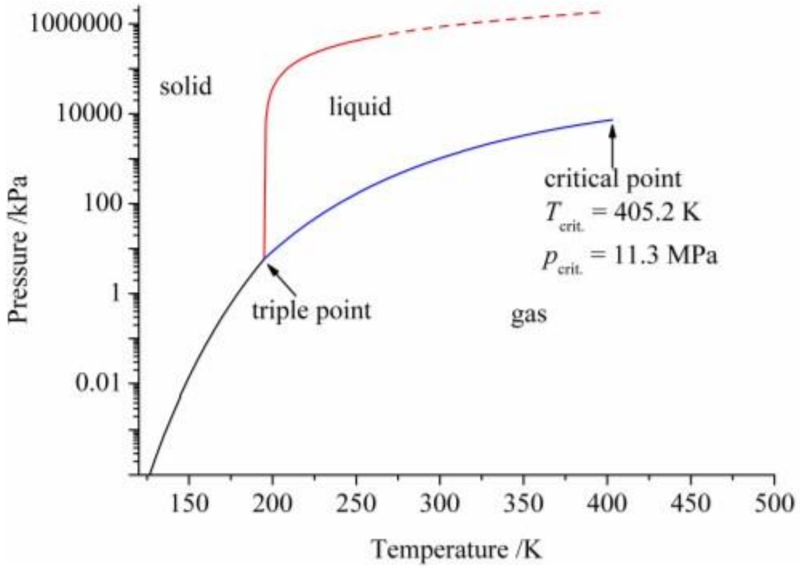

Figure 2-5: Phase diagram of ammonia (Richter & Niewa, 2014)

Transport and Storage

As explained above ammonia is already a commodity and is transported on a large scale nowadays, with well-established infrastructure for the handling and storage of it. Even if ammonia is a gas under atmospheric conditions, transportation is generally performed in its liquid form due to its significantly higher density (Aziz et al., 2020). Liquid ammonia is transported around the world due to large regional unbalances, as the production and demand locations differ. Nowadays, ammonia production is based on natural gas. Green ammonia -based on renewable electricity- can be expected to be produced in areas like the Middle East, Australia, South America and North Africa, which differ from the main demand centers. Western Europe and the US are the two main importers of NH_3 at the moment (ISPT, 2017). Long distance transport is primarily done via sea going vessels but NH_3 is also transported using pipelines, trains and trucks. Vessels that carry ammonia often get up to 60,000 dwt (Laursen, 2018).

Storage is done in two main ways depending on the volume of NH_3 to be stored. Up till volumes of 5000 m^3, the common technique is to store NH_3 pressurized at ambient temperature. Sea going tankers can either compress or refrigerate ammonia or even a combination of the two to keep it in its liquid state. Cooling ammonia down to -33^oC allows the use of unpressurized containers (Avery, 1988). The common practice for large volumes is to store as a liquid at ambient pressure and saturation temperature. To make sure that NH_3 is contained properly, double-walled tank systems are applied. Boil-off gas is also present in ammonia storage. In this case, due to the fact that ammonia is stored at a relatively high temperature (compared to LH_2) and the boil-off rate of ammonia is low (Al-Breiki & Bicer, 2020), re-liquifying the gaseous NH_3 is the assumed process.

In the Netherlands, large storage tanks are already present in Geleen, Rozenburg and Sluiskil (ISPT, 2017). Two of the biggest ammonia tanks in the world are located in Qatar owned by a fertilizing company called QAFCO. They have a 50,000 tonnes net capacity and their dimensions are approximately 50 meters in diameter and 40.5 meters high

(MCDERMOTT, 2014). Based on the above, the transport and storage of ammonia is a big advantage when comparing it with LH_2 for example.

Safety

Contrary to gases like hydrogen, natural gas or methanol, whose vapours are highly flammable, ammonia is not very flammable. A significantly higher concentration of ammonia is needed for an explosion to occur in comparison with gasoline vapour or natural gas (Morlanés et al., 2021). The basic drawback of ammonia is its high toxicity. In the event of a liquid ammonia release into the atmosphere, for example, due to a tank's leakage, a dense cloud is formed. The density of this cloud is significantly higher than air density and therefore it tends to travel along the ground. According to Klerke et al., 2008 liquid ammonia is about three orders of magnitude more toxic than gasoline or methanol in terms of apparent toxicity (the vapour pressure relative to the toxicity at room temperature). Its toxicity, however, has not stopped ammonia from becoming a commodity. Vessels carrying ammonia in bulk travel in and out of the biggest ports in the world without any major concern nowadays, so we can expect that safety will not be a limitation for ammonia as a potential hydrogen carrier. Public concerns may arise if ammonia is stored and/or handled in urban areas and therefore the perception of the public regarding the risks of ammonia is of big interest.

H_2 retrieval / Ammonia Decomposition

This last part of the ammonia supply chain as a hydrogen carrier is the least developed. Ammonia as explained above is widely used worldwide. However, the immaturity of the technology to decompose ammonia is one of the most -if not the most- important limitations in the use of ammonia as a hydrogen carrier (Morlanés et al., 2021). A large scale cracker of ammonia has not yet been developed and only experimental and theoretical applications exist. This is not a result of the immaturity of the technology, but due to the fact that it was not needed to do so until recently. A scale-up of existing ammonia crackers and a possible breakthrough in the technology would be beneficial for ammonia use as a hydrogen carrier. Commercialized ammonia crackers with a production of about 1.5 tn H_2/day exist, but for the case of an ammonia import as a hydrogen carrier much bigger crackers are needed. However, ammonia can be utilized directly as a fuel.

2.1.3 Liquid Organic Hydrogen Carriers (LOHCs)

The concept of Liquid Organic Hydrogen Carriers aims to solve the problems and difficulties of handling and storage of hydrogen in its pure form. As explained in part 2.1.1 liquid hydrogen has extreme requirements and thus it is a challenging cargo both technically and financially. The idea behind LOHCs is to load a LOHC with (green) hydrogen (hydrogenation) and then discharge again (de-hydrogenation) when the need for hydrogen arises. In Figure 2-6 a schematic representation of the concept of LOHCs can be seen. Ideally, LOHCs have to be easily manageable and liquid in ambient conditions (Niermann et al., 2021). Since the 1980s, when research on LOHCs started, various alternatives have been studied. One of the first LOHCs that was studied already some decades ago was Methylcyclohexane (MCH). VOPAK is one of the strategic partners of the German company 'Hydrogenious Technologies GmbH' which is focusing on commercializing hydrogen storage using DBT, another promising LOHC. The use of methanol as a hydrogen carrier has the advantage that widespread infrastructure already exists, while methanol is liquid under ambient conditions. In order to understand the differences between the various LOHCs a brief comparison between the three mentioned above was conducted. The details of this can be found in Appendix A.

Taking into account the LOHCs comparison, the current research will focus on Dibenzyltoluene (DBT), a heat transfer oil used for high temperature applications (Raab et al., 2021). At the same time DBT is definitely looking as one of the most promising alternatives, among others because, after de-hydrogenation, the unloaded DBT can be transported back to the hydrogenation location and reused as a hydrogen carrier, which leads to high-cycle and long-term stability (Kennedy et al., 2019). Furthermore, no CO_2 is emitted when hydrogen is released from the carrier (Deltalinqs, 2019). Given that an import terminal is of interest for this research, DBT is assumed to be produced abroad and transported to the Netherlands, where de-hydrogenation takes place. In Figure 2-6 a schematic representation of the LOHC supply chain can be found. In this Figure it is assumed that green hydrogen is used for the hydrogenation of the LOHC, thus hydrogen is produced using renewable electricity.

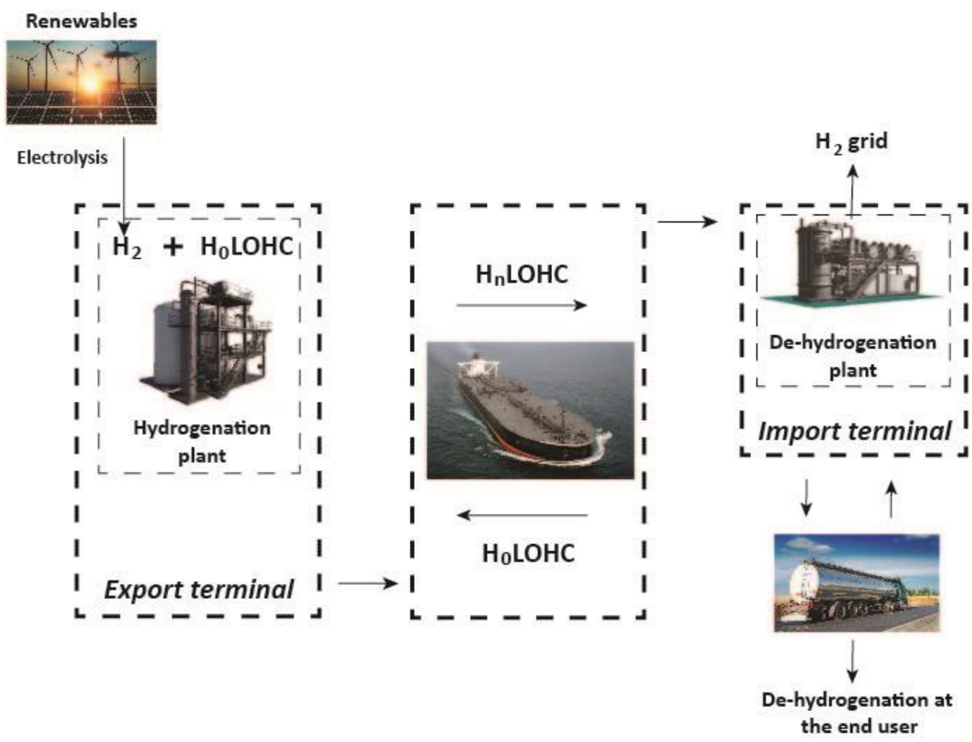

Figure 2-6: The concept of LOHCs (author's illustration)

<u>Properties</u>

DBT is a diesel-like liquid in ambient conditions (boiling point around 320 °C) that is easy to handle. It has a hydrogen density of about 57 kg H_2 / m^3 DBT. This value is the lowest of the three studied carriers.

The production of hydrogenated DBT is realized by an exothermic reaction at around 250 °C and 25-50 bar. In order to do the opposite procedure, namely, obtain the captured hydrogen (de-hydrogenation), an endothermic reaction at around 300 °C and 1-3 bar is needed (Hydrogenious Technologies, 2018).

Property	*DBT*	*Diesel*	*Unit*
Chemical Formula	$C_{21}H_{32}$	$C_{12}H_{23}$	[-]
H_2 %wt	6.23	12.94	[%wt]
Boiling Temperature (1 bar)	380	320	[°C]
Liquid Density (1 bar)	921	820	[kg/m^3]
Energy density	8094	37750	[MJ/m^3]
Flammability limits in air	Hardly flammable	0.6 – 7.5	[%]
Minimum ignition energy	High	20	[mJ]

Table 2-3: Diesel and DBT comparison

Looking at Table 2-3 the similarities between DBT and Diesel are evident. The boiling temperature and density of the two oils are similar, while both are not very flammable. The big difference lies in the energy density, where diesel is significantly more energy dense. This implies that for the same amount of energy production larger volume of cargo is required.

Transport and Storage

Transport and storage of DBT is the main advantage of this carrier. The hydrogenated DBT can be stored and transported using existing, fossil fuel infrastructure (e.g. tankers, terminals), due to the similar properties of DBT to crude oil derivatives. No high pressure or low temperatures are required and thus this LOHC can be handled, stored and transported very conveniently (Kennedy et al., 2019). DBT storage can take place in conventional tanks for products classified as K4. Typically (at least) one tank is required for the hydrogenated LOHC and (at least) one more tank for the de-hydrogenated LOHC while it can be theoretically stored for long periods of time without leakage, boil-off or other hydrogen losses (Niermann et al., 2021). Only in cases where a terminal is used only for storage, all tanks can be used for the hydrogenated or de-hydrogenated DBT. However, the properties between the two (H_0LOHC and H_nLOHC) do not differ and thus the same tanks can be probably used interchangeably.

Waterborne transport can occur via chemical tankers (Class 3[4]) (Kennedy et al., 2019). LOHCs in general exhibit low transport costs, making them even more favorable when long-distance sea transport is needed (Niermann et al., 2021). With small modifications, most existing tankers can be used for DBT transport.

Safety

DBT is a non-flammable oil (Kennedy et al., 2019). According to Hydrogenious it is also non-explosive and is not classified as a dangerous good (Hydrogenious Technologies, 2018). It can be expected that when DBT scales up, similar regulations to the ones that apply nowadays for diesel-like fuels will be implemented. Thus, safety aspects are not going to be a bottleneck for the use of DBT as a hydrogen carrier.

[4] According to IBC code: "A type 3 ship is a chemical tanker intended to transport products with sufficiently severe environmental and safety hazards which require a moderate degree of containment to increase survival capability in a damaged condition."

H_2 retrieval / Dehydrogenation

After the LOHC is transported to the import terminal two basic choices emerge. It should either be de-hydrogenated at a big conversion plant that will be constructed in the terminal (or in the port in general) or de-hydrogenate it at the end-user using small scale release plants. The first option implies that in the port a national or international hydrogen grid exists and thus the released hydrogen from the de-hydrogenation plant will be fed to the grid. In the other case, trucks, barges or trains could transport the hydrogenated LOHC to the end-user, and the de-hydrogenated LOHC back to the import terminal.

It should be noted that de-hydrogenation does not lead to a carrier with 0% as this would require an enormous amount of energy. Approximately 10% of hydrogen remains in the carrier after de-hydrogenation. In addition, the carrier has a lifetime of about 100-200 cycles (defining a cycle as the full chain from hydrogenation to de-hydrogenation), due to a small percentage of side reactions occurring during those processes. After that time the carrier should be sent to a plant for refinement.

According to Hydrogenious, a release plant that can de-hydrogenate about 31 tonnes of LOHC per day is available at the moment. A ten times bigger de-hydrogenation plant (about 300 tn/day) is in the design process. However, even the 300 tn/day plant is far from the required production of a large scale de-hydrogenation plant.

2.1.4 Conclusions based on the review of the three carriers

Based on the information presented above, some basic advantages and disadvantages of the three investigated carriers are summarized in the following table.

Carrier	Advantages	Disadvantages
LH_2	• Lowest energy losses due to conversion • No feedstock is required apart from electricity • Pilot projects are already ongoing and have great momentum worldwide • No big technology barriers	• Challenging to ship due to low density and temperature (-253 °C). Large scale vessels are yet to be developed. • Regulations on the transport of hydrogen in bulk are not yet fully developed. • Boil-off rate is relatively high, and should be managed effectively.
NH_3	• Existing commodity, regulations are not a limitation as large scale ammonia supply chains already exist • Potential to de-carbonize the big fertilizer market • Nautical and terminal safety is not a limitation	• Ammonia decomposition at a low TRL. A technological breakthrough is required to make this option technically and financially feasible. • Toxicity could be a problem for utilization in urban areas. • NO_X emissions if directly utilized.
DBT	• Liquid in ambient conditions, thus easy to handle and no boil-off gas • Storage in typical oil/diesel tanks possible, with minor modifications • Transport using existing tankers is possible • Nautical and terminal safety is not a limitation. • If heat is available for de-hydrogenation, DBT becomes competitive to other carriers, as dehydrogenation cost decreases significantly.	• Low hydrogen density, thus 94% of the cargo is a carrier. • The supply chain is complicated as the de-hydrogenated carrier has to be shipped back • Low TRL of de-hydrogenation • Scale-up of both hydrogenation and de-hydrogenation is necessary. • Significant environmental impacts in case of an accident during sea transport.

Table 2-4: H_2-carriers' advantages and disadvantages

2.2 Regulations and Standards

An overview of existing regulations and standards regarding the three investigated carriers is presented in this chapter. This is important as a harmonized environment between different ports and geographical areas but also between nautical and terminal safety could take away barriers that exist nowadays (Andreasson et al., 2021). Extra attention is paid to liquid hydrogen as ammonia regulations already exist and are applied worldwide so the use of ammonia as a hydrogen carrier cannot be expected to drastically change the existing regulations. Regarding DBT at the moment no regulations exist, however, due to the similarities with diesel-like cargo, it can be assumed that with small changes in already applied regulations the safety of handling, transport and storage of this LOHC can be assured. At the end of this section, a table with a synopsis focusing on the nautical and terminal safety of liquid hydrogen is provided.

NASA has been transporting liquid hydrogen with barges for decades now, however, the tanks are relatively small and the voyage includes mostly inland waterways (NASA, 2020). The first sea going transport of LH_2 in bulk took place in 2021 (around the time this study was conducted), carrying brown hydrogen from Australia to Japan. At the beginning of this project, the involved stakeholders identified that to operate their pilot vessel (called Suiso Frontier) certain guidelines would be required. SIGTTO (Society of International Gas Tanker & Terminal Operators) played an integral part in drawing up the "Interim guidelines for the carriage of liquid hydrogen in bulk" which was attached to the IGC Code (MSC97) and on the 25th of November 2016 was adopted formally by IMO. Any ship carrying liquid hydrogen should comply with those guidelines. The Japanese classification society 'Class NK' has also published guidelines regarding liquid hydrogen vessels, which identify 23 additional safeguards over and above the IGC Code. IGC and IMDG codes as a whole also apply to LH_2 vessels and should thus be taken into account.

For a liquid hydrogen terminal, EIGA Doc 06/19 and Doc 224/20 are relevant. It should be emphasized that EIGA documents are recommendations and the use of those by its members or other third parties is not binding. Apart from the aforementioned EIGA documents, ISO/TC 220 on 'Cryogenic vessels' and CEN/TC 268 on 'Cryogenic vessels and specific hydrogen technologies applications' are important for the storage of liquid hydrogen.

	International	Description
Terminal	ISO/TC 220	Cryogenic Vessels
	CEN/TC 268	Cryogenic Vessels and Specific Hydrogen technologies applications
	EIGA 06/19	Safety in handling, storage and distribution of liquid hydrogen
Vessel	IGC & IGC Code MSC97	Interim Recommendations for carriage of liquified hydrogen in bulk
	Class NK	Guidelines for liquified hydrogen transport

Table 2-5: Regulations and standards overview

3 Nautical safety

This chapter is aiming at answering sub-question B. Using interviews and a questionnaire two different issues are addressed: the nautical safety of a vessel carrying hydrogen in bulk while it sails to an import terminal (but inside or close to a port environment), and the vessel safety when passing through a lock. In Section 3.1 the first issue is discussed, while the second is presented in Section 3.2. The conclusions that can be derived based on both sections are displayed in Section 3.3.

3.1 Nautical safety inside or close to a port

Out of the three investigated carriers, liquid hydrogen is the one for which the biggest questions in terms of safety exist. Ammonia is an existing commodity and DBT is a diesel-like oil and therefore safety of vessels carrying those two carriers is not considered a limitation. For example, in Rotterdam where ammonia terminals exist, vessels carrying NH_3 in bulk are often inside the port. As shown in Table 2-1 hydrogen is very flammable and explosive. Given the fact that no globally applicable regulations exist regarding the transport of hydrogen in bulk, a stakeholder analysis via interviews with Port Authorities and other interested parties is conducted below.

The analysis is conducted using an open-question questionnaire. The exact questions and answers of each stakeholder can be found in Appendix C. The stakeholders/competent authorities that were interviewed in order to gain insights on the regulations related to the nautical safety of hydrogen are the following:

1. Nort Sea Port
2. GNA – Common Nautical Authority
3. Port of Rotterdam
4. Port of Amsterdam
5. Groningen Seaports

Stakeholder/Authoriy	Interviewee	Highlights / Answers / Comments
North Sea Port	Jean-Pierre Maas, Nautical Advisor	• No specific regulations for hydrogen exist or are under development • Due to the Westerschelde, and its competent authority, GNA, cooperation between the involved parties is necessary when new (dangerous) cargo are about to enter the port. • Usually, the two parties, along with RDU Zeeland and VRZ, cooperate in order to develop specific rules. Aiming at consistency between the areas of jurisdiction of each one, they aim at identical regulations. • Usually, some months are required for this procedure, especially if another port in the region has already implemented such kind of rules. • For vessels carrying hydrogen in bulk, a 2000 m visibility will definitely be required and possibly a safety distance from other vessels. In the case that weather conditions are not favourable, the vessel will need to way at an anchorage.
GNA – Common Nautical Authority	Vivian Baetens, GNA Nautical Advisor	• GNA is responsible for the Western Scheldt, with both Dutch and Belgian authorities being part of the decision making process. • They cooperate effectively with the ports (NSP and Port of Antwerp) and other authorities like the fire brigade. • GNA thinks that if any investment is to happen the authority along with the port of interest will know it beforehand so it will have time to do whatever is necessary. They are already gathering information to create their own rules, similar to what they did with LNG bunkering.
Port of Rotterdam	Cees Boon, Senior Safety Advisor / Wim Hoebee, Manager Nautical Affairs and Projects	• PoR is involved in the regulatory process within national and international regulatory authorities to make sure that the PA's perspective will be taken into account. Also, the PA is cooperating closely with other stakeholders (DCMR, Fire Brigade, Tug and Pilot unions, KVNR etc). • PoR thinks that the existing safety framework regarding vessels carrying dangerous goods is sufficient for LH_2 vessels. Some items may need to be adapted, but generally, LH_2 vessels will be handled like every other vessel with dangerous cargo on board. A recent HAZID study, that included 5 example locations, concluded that no real problems can be expected. Only for certain 'busy nautical spots' some extra research is required. • Similarly to LNG carriers, risk mitigation will be focused on avoiding crossing courses. A specified anchorage for LH_2 vessels like the one for LNG will probably be necessary. No specific distances between the vessel and other vessels apply. At the start, some extra safety measures may apply, which may be relaxed later on after gaining more experience. • If an investment decision is made, the next steps would be to conduct a real-time nautical simulation along with dynamic mooring analysis in order to define the optimum mooring configurations. • Generally, the Port of Rotterdam is confident that it can handle any hydrogen-related activities.
Port of Amsterdam	Machiel Noijen, Strategic Policy Advisor / Peter Alkema, Strategic Policy Advisor and Project Manager	• No specific rules for hydrogen vessels. Also no LNG carriers in the port. In 2011 a study was conducted for LNG vessels but the investment was not finalized. • In this kind of cargo, the most important aspect is to avoid crossing courses of two vessels in the canal. • The PoA is looking into hydrogen commercially but no safety studies conducted yet. A study regarding marine fuels including hydrogen and ammonia was executed, leading to sufficient results for all fuels except for ammonia. • Perception of risks by the public is important, especially in PoA which is located close to urban areas. • In case of an investment, safety studies will probably require about a year. • The PoA is in close cooperation with all stakeholders involved, to ensure that the best result, when new rules will be developed.

Groningen Seaports	Geert-Jan Reinder, Dept. Harbourmaster	• No rules for hydrogen vessels yet, but the Port Authority has already started the procedure to develop those by talking to all stakeholders involved. • The Port Authority is cooperating with the Port of Amsterdam and Port of Rotterdam on safety issues, as they are not competing in those. They are aiming at having a common regulatory framework for all hydrogen-related activities. • They think that in the case of an investment decision there will be enough time to develop the required rules, and therefore no limitation can be expected.

Table 3-1: Highlights from communication with stakeholders related to nautical safety of hydrogen vessels

3.2 Safety when passing through a lock

The three locations that will be investigated and compared later on in this study are accessible via normal waterways without the need to pass through a lock. However, if hydrogen becomes a commodity in the following years vessels will certainly need to pass through locks both within the Netherlands but also in other regions (e.g. Belgium or Germany) and more importantly through the Panama Canal. For example in the case of a hydrogen supply chain between Chile and Rotterdam -the Chilean Ministry of Energy and the Port of Rotterdam Authority signed a memorandum of understanding in March 2021- (Port of Rotterdam, 2021) the fastest route for the hydrogen vessel would be through the Panam Canal. For the above reasons, this part of the study is focused on the possibility of the transit of a vessel carrying hydrogen in bulk through locks. This is a topic that is of interest for further study as relevant safety studies have not been conducted until the moment that this research is done.

In this research, the opinions of some involved stakeholders on the issue are discussed. Using a short questionnaire three different authorities were interviewed. Those included the Panama Canal Authority and two locks located in the Netherlands: the locks in IJimuiden and the locks in Terneuzen. The questions focused on the possibility of a vessel carrying hydrogen in bulk passing through the respective lock chamber and the procedure that is expected to be followed in order to develop rules for this kind of situations, and the current situation regarding other dangerous cargo. The questionnaire and the answers in each case can be found in Appendix B. Based on the answers of the three parties the highlights are summarized in the following Table:

Authority / Port	Interviewee	Highlights / Comments
Panama Canal Authority	Confidential source	• At the moment no specific rules for hydrogen vessels exist. • Obviously, no inquiry for a transit of a vessel carrying hydrogen in bulk has happened till today. However, no bottleneck can be expected if the vessel is compliant with international and Panama Canal maritime safety and transit regulations. • No problem can be expected given that international organizations regulate hydrogen vessels. • Similarities with LNG transits can be expected.
Port of Amsterdam	Maciel Noijen, Strategic Policy Advisor and Peter Alkema, Strategic Policy Advisor and Project Manager	• Locks of IJmuiden are owned by RWS but operated by the PoA. Close cooperation between the two parties. • Existing regulations for various cargo, and if two ships are allowed in the lock chamber at the same time, but hydrogen is not part of those at the moment. • If hydrogen vessels are to pass through the locks risk analysis studies will be conducted. • No priority of hydrogen vessels can be expected, but probably they will be alone in the lock chamber.
RWS **– Terneuzen locks**	Rudi Adam, Nautical Advisor	• Locks in Terneuzen owned and operated by RWS. • No regulations exist at the moment. For sea going vessels, international rules and guidelines are followed. • No LNG vessels pass through the locks in Terneuzen. Only LNG barges. • Vessels carrying ammonia also pass through the locks in Terneuzen about once or twice a month, heading at the fertilizer industry of YARA. Those vessels are locked separately and a specific plan for their trip from the pilot station to the berth (and the other way around from the berth to the sea) is determined prior to their arrival. A minimum distance of 10 m, is applied when the vessel is in the lock from the lock gates. However, there is no priority for those vessels compared to typical vessels. • In the case of hydrogen vessels, something similar can be expected. Either way, there are not much more measures to be taken when passing through a lock. The rules that apply today for ammonia vessels will be sufficient. • Public perception of the risks related to hydrogen is important, and often those risks are overestimated.

Table 3-2: Highlights from the communication on the transit of hydrogen vessels through locks

3.3 Comments on nautical safety aspects

The interviews with port and other competent authorities lead to the following observations:

- Authorities are conducting studies and are trying to gather all the useful information for the development of rules related to the transport of hydrogen in bulk in their areas of jurisdiction. However, they are waiting for the industry to take the first step. Thus, regulations may look like a missing part, but in case a supply chain or investment is officially announced, port authorities and other competent authorities, will quickly follow.
- Most nautical and safety advisors do not see LH_2 as something that is more dangerous than LNG. Many of the interviewers were worried more about NH_3, considering it more challenging.
- All parties are in close cooperation with each other, and other organizations like the fire brigade and environmental authorities in order to develop a relevant framework. The Port of Amsterdam and the Port of Rotterdam Authorities along with Groningen Seaports, do not compete on safety and therefore are in close cooperation regarding the development of the regulatory framework of LH_2 vessels and terminals.
- Similarly to LNG, strict rules for liquid hydrogen can be expected in the first applications which will probably be relaxed as time will pass and experience will be gained.
- In general, nautical safety rules are not expected to impose any significant limitations or bottlenecks to liquid hydrogen supply chains.
- For the transit of vessels carrying hydrogen in bulk through locks, where no rules exist at the moment, the strictest rules, similar to the ones implemented for ammonia vessels in Terneuzen locks, can be anticipated.

4 Terminal Design Tool Development

This chapter provides insights regarding sub-question C, explaining how a design tool for the terminal area calculations and layout can be developed. In cases where there is no space limitation, the model can calculate the area of the terminal for a given demand for each one of the three investigated carriers. The model can handle cases where a given terminal boundary is provided as input and produce a conceptual visualization of some basic terminal elements.

4.1 Modelling Concept

To calculate the area required for a specific demand and carrier, one should know how many elements are present in the supply chain each year. The open-source package Open Source Terminal Investment Simulation (OpenTISim), will be used. The package is available at the Github of the Hydraulic Engineering Department of TU Delft (van Koningsveld, 2019). The model is developed in such a way, that every year a comparison between the capacity and the demand is done. If the demand exceeds the capacity of a specific terminal element, an increase in capacity is planned by adding new elements. New functions will be added to the model as part of this research. Those functions will aim at producing graphs for the area requirements, comparing the three carriers, and calculating the demand of a given terminal boundary.

4.2 Overview of the design tool and Model objectives

For a conceptual design of a terminal, the budget and the layout are the two major expected deliverables. Liquid bulk terminals have been in existence for decades now, however, large-scale hydrogen terminals are not yet part of the global energy supply chain. Certain hydrogen carriers can be expected to have similarities with existing fossil fuels (for example diesel with DBT, as shown in Chapter 2) but a hydrogen terminal could among others include hydrogenation and de-hydrogenation facilities, while safety distances could differ from conventional liquid bulk terminals. The study by Lanphen, in 2019 focused more on the cost side of a hydrogen terminal, comparing four different carriers (compressed H_2, LH_2, NH_3, and MCH) and included certain terminal elements in the CAPEX and OPEX calculations. In 2021, Abrahamse investigated the supply chains of hydrogen, starting from the export terminal to the end-user. However, the required area and the terminal layout were not part of the scope in any of those studies. Both of those studies were done based on the existing openTISim Python package.

As hydrogen terminals have not been implemented, hydrogen is usually not a part of existing terminal design tools. Many terminal operators (including VOPAK) aim at adding hydrogen (or a hydrogen carrier) next to an existing liquid bulk terminal that is already fully operating, handling and storing other energy carriers (e.g. LPG, LNG, crude oil etc.). Thus, as part of this study, a design tool for hydrogen terminals is developed, integrated as well in the same Python package. This tool is suitable for designing both a completely new hydrogen terminal at a new location or the addition of hydrogen as a new product next to an existing liquid bulk terminal.

It should be pointed out that it is possible to use the design tool for any of the three investigated carriers. The aim of the design tool can be summarized by the following two main objectives:

1. Calculate the required terminal area, assuming that the area is not a limiting factor.
2. Provide insights for cases where a specified area is given to the tool as input. This includes the throughput that a given terminal area can accommodate and a visualization of the import terminal.

Aiming our attention at Goal 1, one can see that it can be easily achieved as the existing Python package calculates the number of tanks, conversion plants, etc that are needed every year as well as the ones constructed. Therefore, the challenge is to assign proper values to the relevant terminal elements. The assumptions related to those values are elaborated in Section 4.5. After those values were chosen, the model was updated in order to multiply the number of elements with the given area per element and calculate the total terminal area over its lifecycle. After this process is finalized, comparisons between the three studied carriers (LH_2, NH_3, and LOHC-DBT) can be conducted which can provide valuable conclusions regarding the area required for each case. This process is visualized in the following graph. The green boxes in the Figure were already part of the existing openTISim package, the blue ones were input and processes added from the author of this research, while the last two (in red) are the output of the whole process: The required terminal area per year of simulation, and comparisons in terms of area of the three investigated carriers.

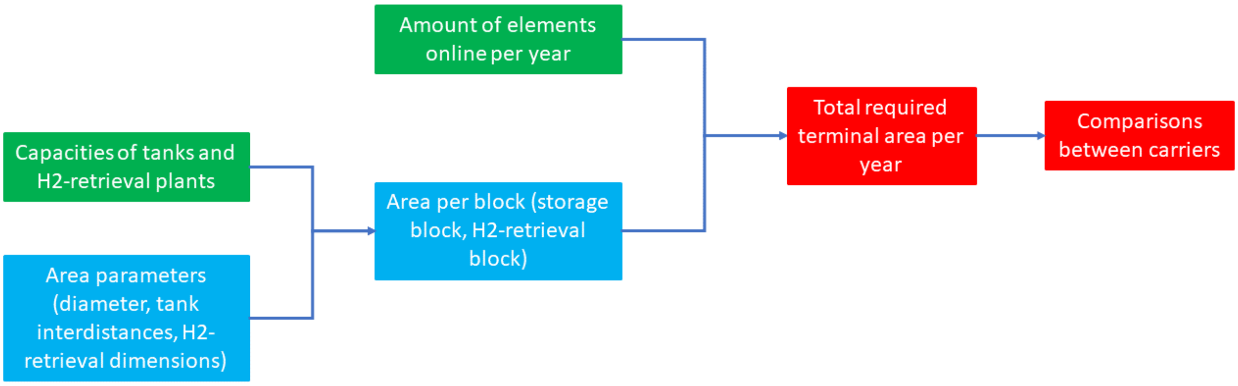

Figure 4-1: Terminal area calculation process

Results of this process can be found in Appendix D, which are validated via a hand calculation in Appendix F. Some validation-test files were also developed to validate the results in an efficient and structured way. Further elaboration on the output and the differences between carriers will be done in the last chapter of this research which will summarize the conclusions.

In cases where the area is a limitation -Goal 2- the tool that is developed as part of this research, can provide the throughput that a given area can accommodate for a given hydrogen carrier. Whether or not the conversion plant is part of the terminal is part of the input that openTISim already required, by defining the exact supply chain. At the same time, the tool produces a visualization of the terminal that includes the tanks and the H_2 – retrieval plants.

The design tool will be developed using Python to produce the terminal layout, for a given terminal boundary. The model will be able to layout the terminal with tanks and H_2-retrieval plants, based on the already existing "triggers" of openTISim: The model is structured is such a way, that a H_2-retrieval plant is added, every time the capacity of the existing ones is not sufficient. The same applies to storage tanks. After the terminal is full, the capacity that the given terminal shape can handle will be calculated based on the number of elements. A validation process will be done using the existing openTISim model from Lanphen and Abrahamse and using the demand that the design tool calculated, perform the investment decisions, cost estimation, and any other of the functions developed by the previous developers of the model. One of the advantages of such a model is that all the automated tasks are performed in the same environment, Python, which is an important asset in software development. In the Table below the scope of the design tool is specified.

Aspects	Included in the tool	Outside of the scope of the tool
Governing parameters and boundary conditions	Throughput, terminal dimensions, and shape	-
Terminal type	Greenfield at a new location, or greenfield next to an existing liquid bulk terminal	Retrofitting of existing infrastructure such as tanks and pipelines
Hydrogen carriers	Liquid hydrogen, Ammonia, and LOHC-DBT	Other carriers like MCH, methanol, etc
Terminal Elements	Storage tanks, H_2 retrieval plants. An assumption will be done for the rest of the elements, as a percentage.	Exact space requirements for roads, offices, pipelines, pump stations, etc.
Storage and H_2-retrieval block definition	Dimensions based on the default values of capacities of tanks and conversion plants	Other tanks and conversion plants sizes

Table 4-1: Scope of the terminal design tool

It should be noted that two main terminal elements are included in the area calculations and visualization. Those are the storage tanks and the H_2 retrieval plants. In the case of a no-space-limited simulation, an approximation of the total area required will be done, by means of a reasonable assumption for the other terminal elements (see Section 4.5). This is done so as to include other parts of a liquid bulk terminal. In the case where a boundary condition in space exists, the visualization will include only the two aforementioned elements but not the rest (pipelines, pump stations, offices, roads, etc). A check will be done at the end of the simulation to make sure that the remaining space is enough for the other terminal elements.

After defining the scope of the design tool, the input and output parameters of the tool are presented in Table 4-2 below.

Task	Input	Output
Boundary condition in space	Terminal dimensions and shape, if area limited	Terminal dimensions and shape as a boundary in space
Type of import terminal (LH_2 or NH_3 or DBT)	Hydrogen carrier specification	Corresponding tanks and terminal elements
Conversion of hydrogen at the import terminal	Existence or not of conversion plant (for NH_3 and DBT) as part of the supply chain	Extra element and area of the conversion plant
Terminal layout specification	Existence or not of conversion plant, design rules	The total capacity that can be handled, terminal layout

Table 4-2: Input and Output parameters of the tool

4.3 Calculating the required terminal area

It is already explained in the previous Section, that the design tool will have the opportunity to calculate the terminal area per year of the simulation in order to acquire the expansion over time. This will be done using the calculations for the number of elements that are already part of the openTISim package, and the inputs as explained in Section 4.5. A graph showing the storage area required, the area required for the H_2 – retrieval, and the total terminal area every year of the lifecycle of the import terminal, will be produced. An example of such a graph is shown below (for a liquid hydrogen terminal), while a hand calculation is provided in Appendix D to validate the results of this specific example.

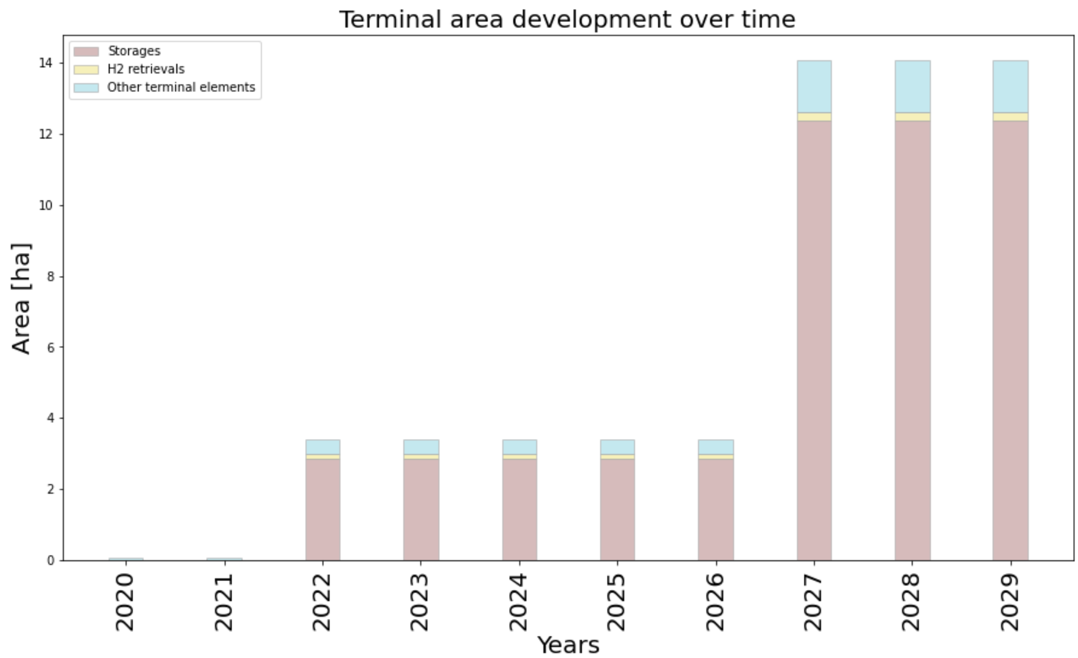

Figure 4-2: Terminal area over time and per element for an LH_2 terminal (openTISim output)

Apart from graphs like the one shown above as an example, the model can plot graphs where the three different carriers are compared for a given demand. In the case below (Figure 4-3), a demand of 200,000 tonnes of H_2 is assumed until 2025 which increases to 1,000,000 tonnes afterwards. The change is only visible in 2027 because the investment decision is made in 2025 and a 2-year construction period is assumed. The exact values and reasoning behind the choice of each one of them, can be found in Section 4.5.

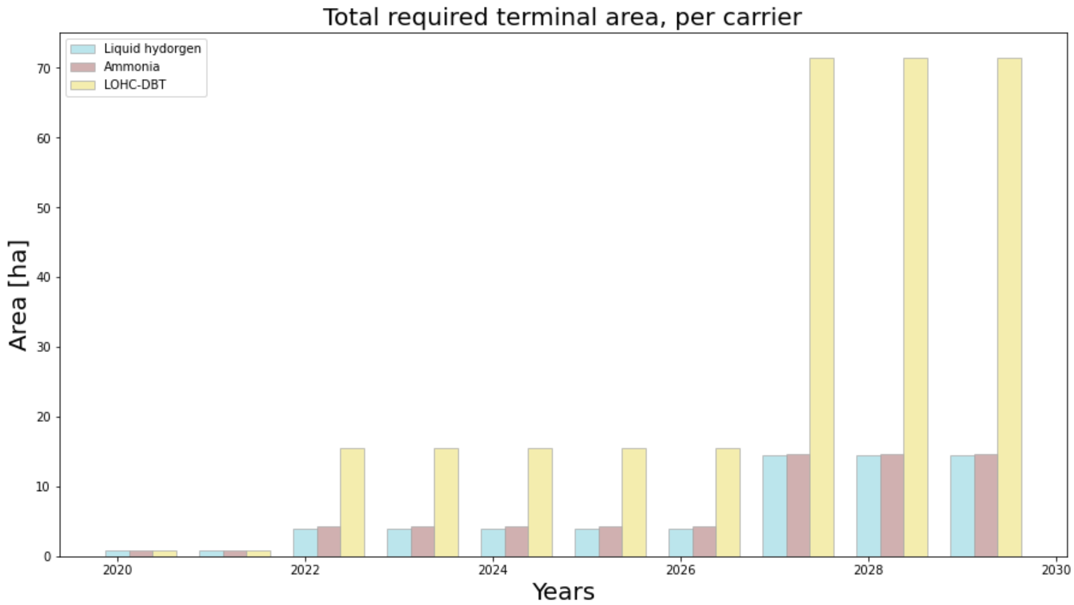

Figure 4-3: Total terminal area, per carrier and year (openTISim output)

4.3.1 Cost of lease of land

The existing openTISim package can generate cash flow data. Based on the area requirements that are explained in Section 4.3, the cost of lease of land will be added so as to be taken into account in the OPEX. Such values are usually based on a concession agreement between a port authority and the terminal operator and vary between countries and ports. Even in the same port, the cost per m^2 and per year can vary based on the exact location, the business case of the client, and the negotiation between the leaser and the port authority. Land availability can also play a role in the price. Bigger and busier ports are often more expensive because the quality of the infrastructure offered is theoretically better. After a personal communication of the author with Groningen Seaports, a price of a maximum of 7.5€/m^2/year (incl. VAT) can be considered for this area (Groningen Seaports, 2021). For a concession of land in North Sea Port, an even lower price of about 6€/m^2/year (incl. VAT) can be considered (North Sea Port, 2021b). For this study, after consulting the experts of PCR a starting value of 10€/m^2/year will be assumed, which is representative for the Port of Rotterdam area. This will be the value to be used as a default value in the model. The user of the openTISim package has the ability to change this value based on the details of the investigated case and the negotiations with the port authority if for example the simulation is conducted for a hydrogen terminal in Groningen Seaports the aforementioned 7.5€/m^2/year (incl. VAT) should be used. In Table 4-3 the above information is summarized.

Port Location	Price in €/m^2/year (incl. VAT)
Port of Rotterdam	10
Groningen Seaports	7.5
North Sea Port	6

Table 4-3: Cost of Lease of land per port

4.4 Terminal layout and capacity

The next challenge that the current study tried to address was the layout of a hydrogen import terminal in a preliminary phase, and the demand that a terminal of given shape and dimensions can handle. It is important to note that for a detailed design phase, this layout is not suitable. A lot more -smaller in footprint- terminal elements must be taken into account for a detailed design, like pumping stations, pipelines, roads, offices, firefighting stations. Thus, the results of the visualization can be used for a first idea of how the terminal will look like and what is the demand that a given boundary can handle. The following are some of the assumptions taken into account:

- No limitations are posed by buildings outside the terminal boundary. In a real-life scenario, a building of a neighbouring terminal may be that close to the boundary that the minimum safety distances from neighbouring buildings are not met.
- The terminal coordinates are given in such a way that the tank farm is located at the 'bottom' of the plot. This may imply, that hinterland connections are on the 'top' as this is where the H_2-retrieval plants will be located.
- The given boundary does not include space for jetties.
- The extra space required for pipelines and roads in between the tanks is assumed to be taken into account in the remaining terminal elements. In general, the length of pipelines is always minimized so as to minimize the CAPEX and OPEX of them. Especially in the case of an LH_2 terminal where the pipelines are costly, special attention must be given to minimizing the total pipeline length. Safety distances between pipelines and other structures may also be required, something not taken into account in this study.
- The storage blocks (tank plus inter distances or containment area) are square. The method allows for future updates, that can generate blocks of other shapes, when no space is available for a square block.

4.4.1 Overview of the process

In this part of the study, the steps of the terminal visualization process are explained. The graph below gives a general idea of how the design tool functions.

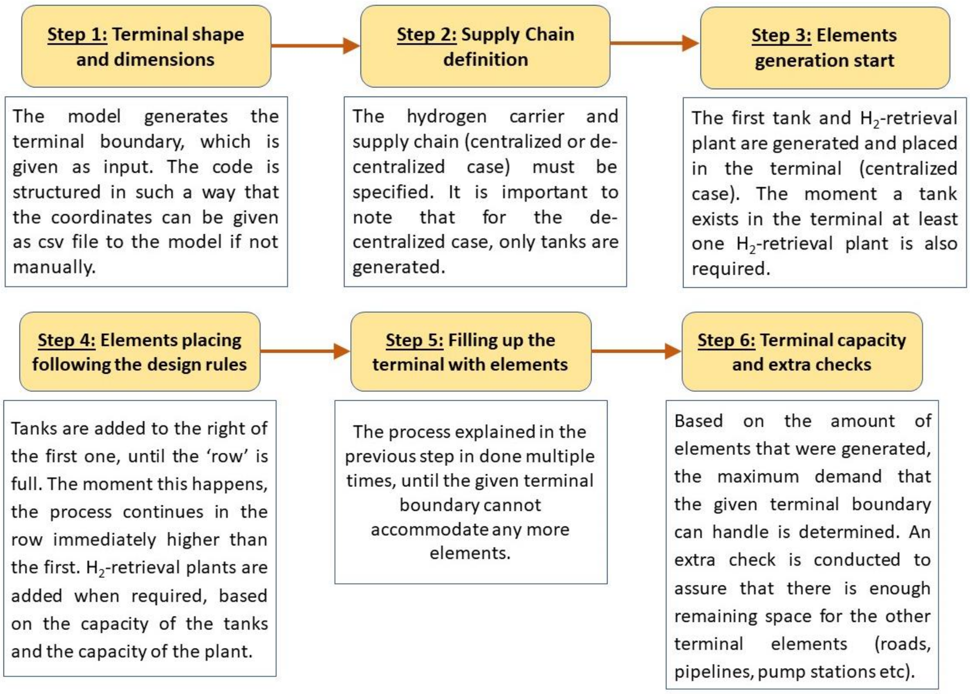

Figure 4-4: Terminal visualization process

Figure 4-5 and Figure 4-6 shown below, can help with understanding the different steps of the process. More specifically, Figure 4-5 shows the terminal just after Step 3, while Figure 4-6 depicts a full terminal, thus the import terminal just after Step 5.

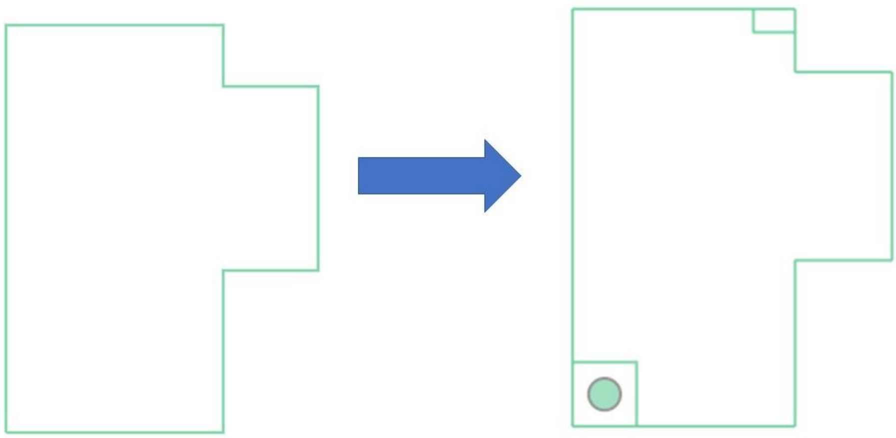

Figure 4-5: The first tank and H_2-retrieval plants for a randomly shaped terminal (carrier: LH_2)

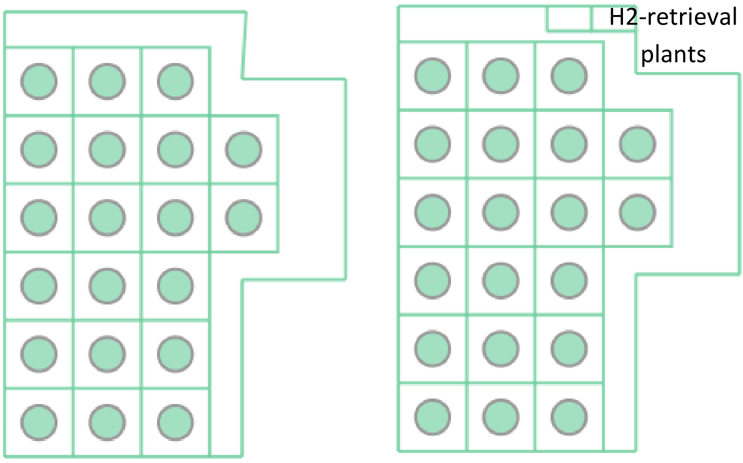

Figure 4-6: Visualization of the terminal, when no more elements can be placed (left: de-centralized case, right: centralized case, Carrier: LH_2)

In the last figure, one can see that the amount of tanks that the liquid hydrogen terminal can “fit” is the same, regardless of the existence of not, of H_2-retrieval plants. This is due to the minimal area that the regasification plants at a LH_2 terminal require.

4.4.2 Capacity calculation

At the last step, the process explained in Part 4.4.1, the capacity that this terminal can handle is calculated (Step 6). This is based on the capacity of the storage tanks and H_2-retrieval plants, taking into account losses due to boil off, losses in the de-hydrogenation process, and dwell time. For the above example of an LH_2 terminal with a centralized supply chain (Figure 4-6 left), the terminal can “fit” twenty storage tanks and two hydrogen regasification plants. The re-gasified hydrogen is then provided to a hydrogen grid. This implies that the terminal can provide to the grid on average 6,350 tons H_2 per day.

Seasonality

The above calculation is based on a yearly averaged demand. This is because the openTISim model is structured in such a way that investment decisions are based on the demand of the terminal each year. However, one can imagine that this demand may have seasonality with differences during a year. This is relevant especially for the dimensioning of the retrieval plants. Similar considerations are done when designing the gate of a container terminal, which is presently done for the statistically busiest hour of the year (van Koningveld et al., 2021). Seasonality is also present in LNG demand, mainly is cases where natural gas is used for residential heating (U.S. Energy Information Administration, 2020). The daily demand can be even four or five times higher for residential and commercial consumption during the winter. On the other hand, power generation presents a summer peak, while demand for industrial use is relatively stable throughout the year (see Figure 4-7).

In natural gas grids seasonality patterns are often solved by large scale storage in empty gas fields or salt caverns and do not have to be considered during shipping and terminal storage planning. As a result, based on the intended use of hydrogen, similar techniques could be used for seasonality patterns in hydrogen demand. Further research on the seasonal variations of potential hydrogen use is advised.

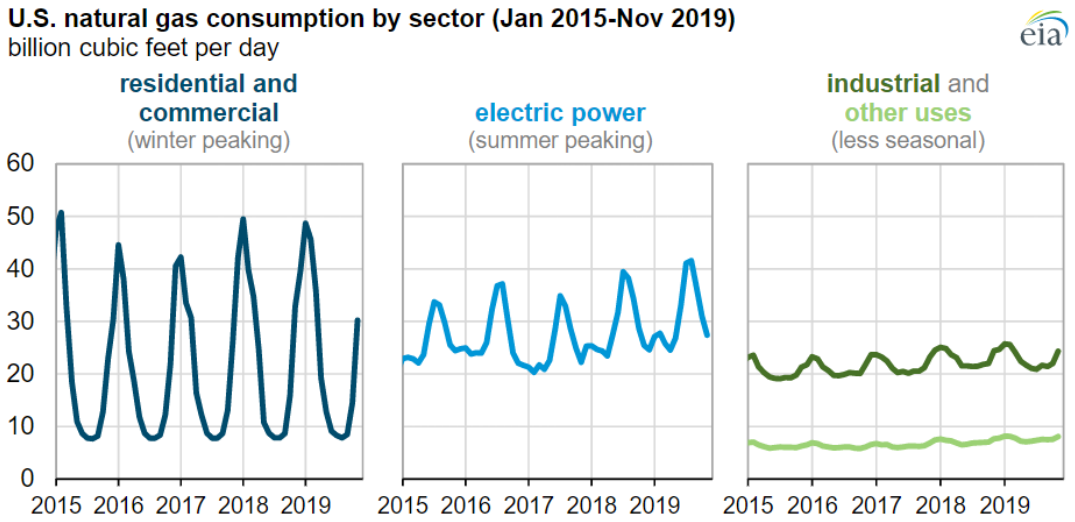

Figure 4-7: Natural gas consumption by sector ((U.S. Energy Information Administration, 2020)

4.5 Design rules and input parameters specification

To produce a terminal layout the terminal elements must first be specified, for each one of the three investigated alternatives (LH_2, NH_3, DBT). After determining the elements their input parameters and the design rules have to be defined and provided to the tool. For example, the area of a storage tank along with the safety zone around it must be defined along with the way the elements are produced and put in place (design rules). As explained above, two terminal elements are taken into account for the calculation of the terminal area and the conceptual terminal design: Storage tanks and H_2-retrieval plants.

As part of this research, the new features 'diameter' and 'height' will be given to the storage tanks. Additionally, the height of the bund wall around the tank will be specified, but only for the DBT case where it is relevant. Based on those numbers and the design rules, the block square per investigated carrier can be determined. For the H_2 retrieval plants, the features 'length' and 'width' will be given. The reasoning behind all the choices can be found below, while a summary of all the values can be seen at the end of this Section, in Table 4-4.

Tank dimensions: Some basic information related to the storage of the investigated hydrogen carriers are presented in Section 2.1. Based on this literature review and the default values for the tank capacities already existing in openTISim for the three investigated carriers the tank dimensions (diameter and height) had to be defined.

- For LH_2 spherical tanks were assumed. In order to store 3,550 tonnes of liquid hydrogen, a diameter of approximately 46 m is required. This number is the input value to be used in openTISim.
- For NH_3 cylindrical double-walled refrigerated tanks are assumed. Ammonia is a relatively light cargo (in comparison to oil products for example) and thus ammonia tanks are usually higher. A height of 18.5 m is assumed leading to a diameter for ammonia tanks of 59 m in order to store 38,500 tn of NH_3. The dimensions of a cylindrical tank are optimised based on various aspects like the availability of land, soil characteristics etc. The dimensions assumed in this study are -among others- based

on examples of ammonia tanks as provided by PCR and other interviewed engineering companies.

- Cylindrical tanks for oil products higher than 20 m are usually avoided as the soil bearing capacity becomes a limiting factor and deep foundations are required. Thus, cylindrical tanks for DBT are assumed to be 19 m high. Given that they should be able to store about 52,850 tn of DBT, a diameter of 63 m is necessary.

Tank inter distances / Bund walls: Distances between tanks is always crucial in liquid bulk terminals. Especially for LH_2, the allowable distance will lead to the 'storage block'. This is because in case of a leakage, liquid hydrogen will evaporate very fast and thus no bund walls are required.

- According to NFPA 30 for tanks with flammable and explosive cargo with a diameter larger than 45 m, a distance of at least 1/6 of the sum of the diameters of the two neighbouring tanks is required. This would imply that for LH_2 tanks with D = 46 m as defined above, a minimum distance of 16 m between the tanks can be defined. However, this rule is not defined specifically for liquid hydrogen tanks. Thus, the author's assumption is that similar rules and decisions to those that apply to other flammable and explosive cargo, like LNG can be used. At the Gate Terminal in the PoR, the three existing LNG tanks have an inter distance of about ¾ of their diameter. In the Sines LNG Terminal in Portugal, the distance between the tanks is ½ of the diameter, while in Fos-sur-Mer, France it is ¾ of it. Based on all the above, the assumed inter distances between two neighbouring LH_2 tanks for the purpose of this study will be D/2. Obviously, this choice has to be validated in the future, using QRA tools, or when new liquid hydrogen standards will be introduced. In case the updated value is different it is relatively easy to adjust it in the model calculations.
- According to Mannan, (2005) due to the fact that ammonia evaporates fast, the presence of a bund wall is virtually irrelevant (Figure 22.23 of Mannan, 2005). Thus the required safety distance between two tanks is the dominant factor. A minimum distance between the tank and other activities of 25 m is required according to PGS 12 (PGS 12, 2020), but this distance is lower than half the diameter of the tank and thus it is not affecting the definition of the 'ammonia block'. However, in a general case where half a diameter would be smaller than 25 m, a distance of 25 m between two tanks should be considered.
- For DBT tanks, the 'storage block' is governed by the required area in the case of a leak. The DBT tanks are 63 m wide and 19 m high. For a detailed design, the spillage dikes around the tank farm would be calculated in detail. For simplicity, it is assumed that each spillage area should be able to contain 70% of the tank's volume. This value is an approximation as for a detailed design, the exact number of tanks that form a 'tank group' must be known, which is not possible in this phase of a design. Assuming a dike height of 4 m, one determines the dimensions of the bunded area. In the case of a square bund area, the dimensions are 121 x 121 m. This leads to a distance close to 1 diameter (about 58 m), and thus the requirement for a safety distance of 1/3 of the diameter is fulfilled.

H_2 – retrieval plants' area: For the gasification / de-hydrogenation plants some basic information was provided in Section 2.1, and with the default values as those defined in the studies of Lanphen and Abrahamse the areas per carrier are assumed based on the following:

- For LH_2 the gasification process is expected to be almost identical to LNG. This assumption is based on the literature and validated by the study on the retrofitting of the LNG-Peakshaver to be fit for processing LH_2 (Kolff, 2021). For LNG gasification many different techniques exist. One of the easiest and widely used -especially for gasification facilities with proximity to the sea- is the Open Rack Vaporizer (ORV) as explained in Part 2.1.1. The default value of the gasification facility production is 137 tn/day. An ORV for LNG with a production of 150 tn/hour, would have a footprint of about 17x11 m (= 187 m^2) (Hisada & Sekiguchi, 2004). The ORV's constructed at the Gate Terminal in the PoR, assuming a seawater temperature of 10 °C has a capacity of 50 tn/hour. Taking crude measurements from Google Earth each one of those ORV's has a footprint of about 15x25 (= 375 m^2) which is significantly higher than the theoretical value acquired from Hisada & Sekiguchi. For the purpose of this research, the assumption of the hydrogen gasification plant footprint will be based on the ORVs of the Gate Terminal. Therefore for a capacity of 137 tn/hour, about three ORVs like the ones at the Gate Terminal are needed and given that these kinds of facilities can be installed in parallel the three ORV's will be of 45x25 m.
- For the ammonia decomposition plants please check Part 4.5.1.
- For the de-hydrogenation of DBT and after communicating with Hydrogenious, two values for the footprint of two different de-hydrogenation plants were acquired. A plant of 1.5 tn/day will have a footprint of 17x17 m, while a plant 10 times bigger (15 tn/day) will have a footprint of about 40x40 m. Assuming a simple power-law based on the above values, and taking into account the default value of the production of the H_2–retrieval plant for DBT, the dimensions of the plant are assumed to be 197x197 m.

Other terminal elements: In addition to the two aforementioned elements (storage tanks and H_2 – retrieval plants, a liquid bulk terminal has many more elements. Those include elements whose area is generally independent of the terminal size (offices, parking, pumping stations etc) and others like areas for pipelines and roads which significantly increase when the terminal area increases. This was also validated using already designed terminal plots, provided by PCR, and Google Earth measurements. For the area of offices and parking, 5,000 m^2 were required on average. For pumping stations, the average required land was 2,000 m^2. The terminal-size dependent elements were estimated at 10% of the total terminal area. Thus, the area calculated for the two basic elements, plus the constant numbers of offices and pumping stations, will be divided by 0.90 to acquire an estimated higher number that will include all other elements.

4.5.1 The special case of Ammonia Decomposition Plants

In Chapter 2, the fact that large scale ammonia decomposition plants do not exist is introduced. For the area calculations, a value of the required area of one plant is however crucial. Literature research was first conducted without any useful values found. It became clear that even if values for the production of small-scale ammonia decomposition can be found, their footprints are not available, as at this scale they are irrelevant. The author then tried to find the desired value by contacting companies from the industry that may have a crude estimation.

After personal communication and meeting with Proton Ventures[5] (Proton Ventures, 2021) a detailed and official requisition document was drawn by the author (the requisition document can be found in Appendix H). Even in this case, however, the company answered that no clear answer on the dimensions of a large-scale ammonia decomposition plant can be given as a lot of ambiguity regarding those plants still exists.

The above implies that at the time that this study is conducted, the acquisition of a value of the required area for the decomposition of ammonia on a large scale does not seem to be a viable solution. On the other hand, there are many indications that the direct use of ammonia as fuel is gaining momentum in the last decade (Erdemir & Dincer, 2020; Kobayashi et al., 2019). As a result, the decomposition of ammonia in the terminal itself will be excluded from the scope, and it will be assumed that ammonia will either be utilized directly in ammonia combustion engines or decomposed at the end-user using small scale decomposition plants. In Table 4-4 found below, the column for the ammonia retrieval plant will be thus left blank.

It is important to note that the option of calculating the required area of an ammonia terminal including decomposition plants or producing a visualization of it given a terminal boundary, is possible in the model as long as a proper input value is given. This is because the model can calculate the area including decomposition plants for liquid hydrogen and LOHC-DBT terminals anyway. This implies that in the future when a representative value of a large-scale ammonia decomposition plant can be acquired, it can be directly added to the model without any major modifications.

[5] Proton Ventrues delivers innovative green engineering and turnkey solutions for world-scale storage terminals, ammonia production units and other process applications.

4.5.2 Summary of the input values

In the following table, the above information is presented altogether.

Terminal Element	Feature	LH_2	NH_3	LOHC - DBT
Storage Tank	Type of tank [-]	Spherical	Cylindrical double-walled	Cylindrical with dome roof
	Capacity [tn]	3,550	34,130	52,850
	Capacity [m^3]	50,350	51,000	58,000
	Diameter [m]	**46**	**59**	**63**
	Height [m]	**46**	**18.5**	**19**
	Tank inter distance [m]	**D/2**	**D/2 or 25 m**	**Based on the containment area**
	Bund wall height [m]	**-**	**-**	**4**
H_2 - Retrieval	Type of H_2 - retrieval	LH_2 gasification	Ammonia cracking	DBT de-hydrogenation
	Capacity [tn carrier/day]	3,288	-	17,808
	Capacity [tn H_2/day]	3,288	-	1,104
	Area [m^2]	**1,125**	**-**	**38,800**
	Dimensions [m x m]	**45 x 25**	**-**	**197 x 197**
Other terminal elements	**Area for offices, parking [m^2]**	**5,000**	**5,000**	**5,000**
	Area for pumping stations [m^2]	**2,000**	**2,000**	**2,000**
	Area for things directly related to the terminal's size (space for roads, pipelines etc)	**10 % of the total**	**10 % of the total**	**10 % of the total**

Table 4-4: Input parameters

5 Multi-Criteria Analysis

This chapter aims at answering sub-question D. Firstly, an introduction to the methodology is presented, explaining the way it works and the reasoning behind this choice. Then the indicators/criteria that will be taken into account are determined, decided along with an evaluation framework for each one of those. The next step is to specify the alternatives that will be considered in the Multi-Criteria Analysis. Lastly, the investigated alternatives can be scored, and the best scoring alternatives will be summarized. At the end of this chapter, an analysis on the hinterland connections related to hydrogen supply chains and the way to quantify this criterion is provided along with some other considerations that one should take into account but are not included in the MCA method.

5.1 Introduction

Multi-Criteria Analysis (MCA) techniques have throughout the years proved to be useful support tools especially when dealing with problems where different aspects have to be taken into account. For example, financial, technological, environmental, and social aspects often need to be included in the decision-making process. In other words, MCA techniques are able to capture the plurality of dimensions involved in decision-making problems (Oosterwegel, 2018), an advantage that a cost-benefit analysis -for example- does not have. Some of the most crucial advantages of an MCA are (Finco & Nijkamp, 1997):

- Taking into account different criteria which altogether play a vital role in the assessment
- Taking into account qualitative and quantitative aspects simultaneously
- Allowing for structured communication between various stakeholders (policy-making bodies, decision-makers, etc)
- By including scenario experiments in the analysis possible future uncertainties can be taken into consideration

Various methods have been developed since MCA started growing. Most of those follow a similar approach where first of all criteria and alternatives have to be defined, then numerical values and/or weights should be attached to them, and lastly, after processing the numerical values the ranking of each alternative is determined (Triantaphyllou, 2000).

5.2 The method

For the purpose of this research, a method will be developed to provide a holistic approach to a decision-making problem related to hydrogen import terminals. The method will be aimed at determining the best alternative between several alternatives, each one of which will be defined as a combination of a location and hydrogen carrier. The method will be able to compare, score and provide insights on a decision between for example a liquid hydrogen import terminal in Rotterdam and a LOHC-DBT import terminal in Eemshaven. It must be clear that the method aims at being a generic one, where different combinations of locations and hydrogen carriers can be compared. It will be suitable also for comparing different locations but only one carrier (for example comparing two liquid hydrogen import terminals in different locations), as well as comparing different carrier alternatives in the same location (for example an ammonia and LOHC-DBT terminal in the Port of Amsterdam). The method will be focusing on hydrogen terminals to be developed next to an existing liquid bulk terminal. This implies that it will not be suitable for pure greenfield terminal development, as certain criteria will be closely related to the existing services that the terminals accommodate. Nevertheless, it can be used as the base of an updated method to be used for greenfield projects, something which is out of the scope of this study.

5.3 Selection of indicators

The first step is to specify which indicators will be taken into account in the decision-making method. The decision on where to develop a hydrogen terminal and which carrier is the best alternative is a very complicated problem, where various aspects can play a role. An investment decision is always based on a business case and thus on costs (CAPEX and OPEX) and revenues. However, building a financial model for each option is both challenging and out of the scope of this research (insights can be gained from the openTISim cash flows). Therefore, various other aspects of a decision-making problem are included in the Multi-Criteria Analysis conducted later on in this Chapter. The criteria can be divided into categories with each category consisting of 2-4 criteria. The categories and the corresponding criteria of each one, as well as the reasoning behind the choice of each criterion, are explained below.

A. Operations:

1. Possibility to use existing infrastructure: In the long term when fossil fuels will not be part of our energy system, existing fossil fuel infrastructure will be either demolished or retrofitted to handle new energy carriers. Assuming that the second option (retrofitting) is preferable, then the possibility to use the existing terminal infrastructure by the new hydrogen carrier can be part of the decision-making process.
2. Relationship of the new cargo to the existing services: Given that this research is focusing on adding a hydrogen terminal next to an existing liquid bulk terminal, the relationship between the new cargo and the existing services that the terminal provides is of importance. This is mainly connected to the daily operations of the terminal. If the new and the existing cargo are similar, the existing terminal personnel will easier adapt to the new era.

B. Safety:

3. Carrier safety: Based on the Literature Review of Chapter 2 it is clear that the differences between the carriers in terms of safety can be significant. Various studies conclude that safety can be a limitation. Safety is one of the points that this study is focusing on, and therefore including the safety of each hydrogen carrier in the MCA is an obvious decision.
4. Nautical safety / Readiness of the Port Authority: In Chapter 3 the views of different stakeholders and mainly Port Authorities were investigated, focusing on nautical safety aspects. Of course, the questions lie mainly on vessels carrying hydrogen in bulk as ammonia tankers are already part of the marine environment and DBT-carrying vessels are not expected to need any extra safety measures. Given that none of the interviewed ports has determined the exact rules required for a hydrogen vessel to sail in it, the readiness level of each port in the case of a hydrogen-related investment is taken into account.

C. Infrastructure and current Port situation:

5. Hinterland connections: As in almost every port-related project the connection to the hinterland is vital. For the transport of LH_2, NH_3, and LOHC-DBT to the hinterland, various possibilities exist, but for this report transport by pipeline,

barge, rail and trucks are taken into account. The significance of each modality is very much dependent on the hydrogen carrier. A further elaboration on the relationship between the different modalities and the three investigated hydrogen carriers is presented in Section 5.7

6. Proximity to end-users and partnerships: Many ports around the globe are trying to develop a strategy in order to become hydrogen hubs. A hydrogen import terminal is boosted if other hydrogen-related projects are planned in the same port environment and if potential clients (industrial clusters etc) are located nearby. A 'manual' on how to evaluate a port's position with relation to end-users, for hydrogen-related projects can be found in Appendix G. Using this criterion possible differences between locations regarding their strategic position will be taken into account.
7. Land availability: Following the development of the design tool as explained in Chapter 4, it became clear that hydrogen terminals will require more space than conventional liquid bulk terminals due to -among others- the dehydrogenation plants if a hydrogen carrier is chosen and the large volumes of hydrogen that a hydrogen terminal will need to store and handle. Using the insights gained in the previous chapter and the comparison of the area requirements for each hydrogen carrier, and the land availability in the location of interest, the scoring of each alternative will be determined.
8. Draft limitations: When designing an import (or export) terminal a fundamental requirement is that the design vessel must be able to approach the quay wall or jetty. If the available draft at the access channel of the port or the existing depth if one is referring to an existing terminal is not sufficient then this implies extra costs and a significant barrier for the project. This criterion is aiming at comparing the available draft at each terminal location with the expected draft of the vessels per carrier.

D. Technology:

The literature review on the state of the art of storage, handling, and retrieval of each one of the investigated carriers (Chapter 2) made clear that technological limitations exist in many parts of the supply chains. As this study is focusing on the import terminal where two are the main components (storage and H2 – retrieval) the Technology Readiness Level (TRL) of those two will be taken into account:

9. TRL of storage: Technology Readiness Level of storing the specified carrier.
10. TRL of large-scale de-hydrogenation: Technology Readiness Level of de-hydrogenating (if applicable) the specified carrier. It must be noted that this criterion is taken into account only if the studied supply chain is centralized (de-hydrogenation takes place at the terminal and not at the end-user).

Each alternative is in fact a combination of a location and a carrier. Therefore, the criteria can be divided into carrier-specific, location-specific, and others. This means that a carrier-specific criterion would have the same value for all the alternatives where this carrier is included. For example alternatives V.NH3, E.NH3, and R.NH3 will have the same value of the indicator "TRL of carrier's storage" as the Technology Readiness Level of ammonia storage is not affected by the location of the import terminal. The same applies to a location-specific indicator. Lastly, the evaluation of most indicators (six out of ten) is based on both the carrier and the location and thus the characterization carrier or location-specific does not apply to those. The above is summarized in the following Table, where the category of each criterion can be seen along with the remark if it is carrier or location-specific.

Category	Criterion	Remark
Operations	1. Possibility to use existing infrastructure	-
	2. Relationship of the new service to the existing service	-
Safety	3. Carrier Safety	Carrier specific
	4. Readiness level of the Port Authority in terms of nautical safety	-
Infrastructure and current Port situation	5. Hinterland Connections	-
	6. Proximity to end-users	-
	7. Land Availability	-
	8. Limitations due to available draft	-
Technology	9. Technology Readiness Level (TRL) of carrier's storage	Carrier specific
	10. TRL of the carrier's H2 - retrieval on a large scale	Carrier specific

Table 5-1: Categories, criteria, and remarks

5.4 Quantification of indicators

After defining the criteria, the way to evaluate them by means of a scoring system has to be defined. Most MCA methods, use experts' consultation to provide the quantification of the indicators, usually via questionnaires. In this method, a four-scale scoring system is used, so each criterion can take a value of ++, +, -, or --. This decision was made based on discussions with PCR experts and literature review. A similar method of quantification was used by Ares Moreno, (2018) for a green port development location study. It is an easy and relatively objective way to quantify the relevant criteria. In the following Table an example of how one of the criteria (Carrier safety) is evaluated, is presented. The exact way of each criterion's evaluation framework is explained thoroughly in Appendix E. This framework gives the user a level of subjectivity when scoring. However, as with most MCA methods, different experts can be expected to score the same alternatives, differently even if they use the same method.

Carrier safety	++	Carrier is not flammable, not explosive, not toxic to humans.
	+	Carrier has two of the below characteristics (for example it is flammable but not explosive or toxic).
	-	Carrier has one of the below characteristics.
	--	Carrier is flammable, explosive and toxic to humans.

Table 5-2: Example of criteria evaluation.

5.5 Specifying the alternatives

In this research, the alternatives are the different carriers (LH_2, NH_3, and DBT) per location. Given that three existing ports and three different hydrogen carriers are considered, a set of nine alternatives exists. In the table below (Table 5-3: Studied alternatives) the nine alternatives are displayed and given a "code". The code will be used later on when referring to an alternative for practical reasons. It is important to note, that for the Port of Rotterdam, different locations may be considered based on the investigated carrier. This is because, the port area is vastly bigger than a typical port, with a variable draft and surroundings, while

VOPAK has facilities in different areas of the port. Thus, a reasonable assumption will be made based on interviews and discussions with different stakeholders on the most probable location for each carrier.

Code	Location	Hydrogen Carrier
V.LH2	Vlissingen	Liquid Hydrogen (LH_2)
V.NH3	Vlissingen	Ammonia (NH_3)
V.DBT	Vlissingen	LOHC-DBT
E.LH2	Eemshaven	Liquid Hydrogen (LH_2)
E.NH3	Eemshaven	Ammonia (NH_3)
E.DBT	Eemshaven	LOHC-DBT
R.LH2	Rotterdam – Gate	Liquid Hydrogen (LH_2)
R.NH3	Rotterdam – Gate	Ammonia (NH_3)
R.DBT	Rotterdam – Botlek	LOHC-DBT

Table 5-3: Studied alternatives

As explained above, the aim is to specify the best alternative or alternatives based on their score. The indicators that will help acquire the best alternative are elaborated in the following section. It should be noted that it is not possible to take into account every aspect that can play a role in an investment decision. Thus, when referring to “best alternative”, the author always implies the best one, strictly based on the chosen criteria and the defined evaluation framework.

5.6 Alternatives scoring and best scoring alternative

The evaluation framework as explained in Appendix E gives a relatively objective overview of how to quantify the different indicators. The exact scoring of each one per alternative is explained in Appendix F and later in this chapter. In this section, the scores are summarized and the best scoring alternative(s) are determined.

Table 5-4 shows the score of each alternative per criterion. One can see that while in Rotterdam the three carriers seem to have relatively close scores, for Eemshaven the score for LH_2 and NH_3 is low compared to the score for a DBT terminal. In Vlissingen LH_2 and NH_3 have a significantly higher score than the DBT terminal. The highest scoring out of all the nine alternatives is the R.DBT: A DBT terminal in the port of Rotterdam (Europoort), with a score of 10+. V.NH3, E.DBT and R.LH2 are very close, all with a score of 9+.

#	Criterion	V.LH2	V.NH3	V.DBT	E.LH2	E.NH3	E.DBT	R.LH2	R.NH3	R.DBT
1	Use of existing infrastructure	-	+	--	--	--	++	-	+	++
2	Relationship of the new service to the existing service	+	+	--	--	--	++	++	+	++
3	Carrier Safety	-	--	++	-	--	++	-	--	++
4	Readiness level of the Port Authority in terms of nautical safety	--	++	+	--	+	+	+	++	+
5	Hinterland Connections	++	+	+	++	+	+	++	++	+
6	Proximity to end-users and partnerships	+	++	+	+	+	+	++	++	+
7	Land Availability and Requirement	++	++	+	++	++	+	-	-	--
8	Draft limitations	++	++	--	+	++	--	++	++	++
9	Technology Readiness Level (TRL) of carrier's storage	+	++	++	+	++	++	+	++	++
10	TRL of the carrier's H2 - retrieval on a large scale	++	--	-	++	--	-	++	--	-
Score		**7+**	**9+**	**2+**	**2+**	**1+**	**9+**	**9+**	**7+**	**10+**

Table 5-4: Scoring per alternative

In the model developed for the MCA, and in the scoring of the above table, all criteria weights are assumed as one. Therefore, one could easily make up specific scenarios where - for example- safety criteria or technology related criteria etc. are given higher weights. For the purpose of this study, the general scenario where all weights are kept equal to one is considered sufficient. In order to gain a better understanding, all the above information on how the MCA is structured, is schematized in the following Figure.

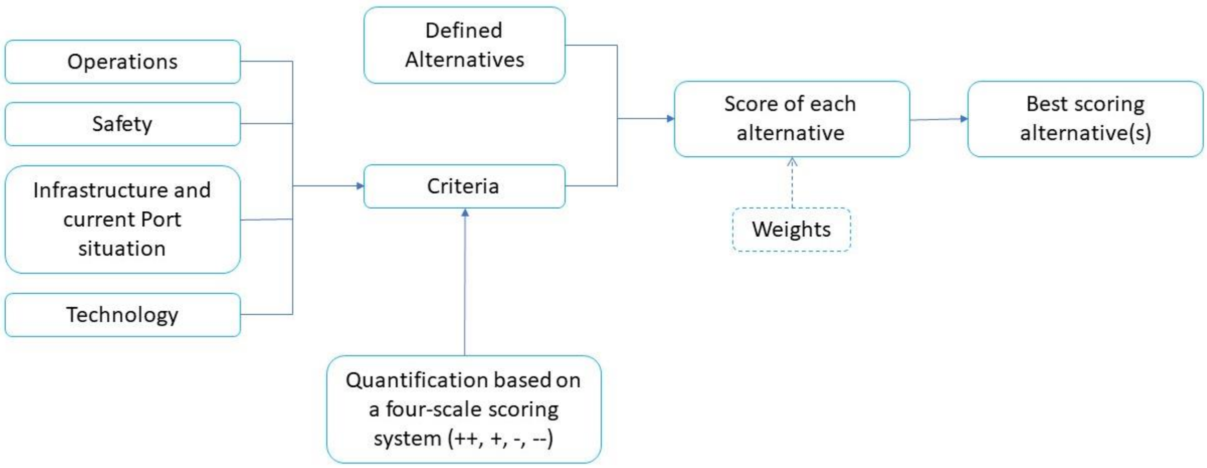

Figure 5-1: MCA schematization

5.7 Hinterland Connections

Hinterland connections is a very important and complex aspect of the hydrogen supply chain. That is the reason, that this Section is dedicated to a more elaborate analysis of the transport of hydrogen to the hinterland. As mentioned in Section 5.3 four different modalities are taken into account in this study, pipeline, barge, rail and truck. For each of the three investigated carriers, the significance and prospects of those four transport options are summarized below, in Parts 5.7.1 to 5.7.4. Based on that information and the specific characteristics of each port location, the scoring of each case is determined. It is important to note that a case-by-case approach is followed in this study, due to the complexity of the topic of hinterland connections for hydrogen carriers. The score of each case is given in Part 5.7.5

5.7.1 Pipeline

Pipelines are traditionally used in order to transport liquid and gaseous fossil fuels. Based on the work of Abrahamse, (2021), it is assumed that gaseous H_2 and NH_3 pipelines are relevant for transporting large volumes of cargo to the hinterland. However, as of today, only small scale ammonia pipelines exist in the Netherlands (Zomer, 2019) and a 140 km hydrogen pipeline network managed by Air Liquide. Concrete plans do exist towards building a system of hydrogen pipelines throughout the Netherlands ("Hydrogen Backbone"), by reusing natural gas pipelines and constructing some new hydrogen pipelines in specific cases (Gasunie, 2021a). It should be noted that the construction of ammonia pipelines could lead to serious social concerns. When it comes to LOHC-DBT pipelines, theoretically, the use of existing oil pipelines is feasible, but it is not considered since the dehydrogenated LOHCs have to be transported back to the terminal, leading to a double pipeline (Abrahamse, 2021).

5.7.2 Barge

Barges and inland vessels are also traditional ways of transporting cargo to the hinterland. A big advantage of inland transportation is the fuel efficiency of a barge is better than that of a truck (Abrahamse, 2021). All three hydrogen carriers (LH_2, NH_3 and LOHC-DBT) can potentially be transported using barges. Similar to ocean-going vessels that carry liquid hydrogen in bulk, liquid hydrogen barges do not exist as of 2022. However, similarities can be expected with barges carrying LNG, with the main difference being the cost (Abrahamse, 2021). Transport of ammonia can be done using chemical tankers similar to those in use for LPG (Zomer, 2019). For DBT inland transport, oil tankers can be used due to the similar characteristics of this LOHC with oil products (Reuß et al., 2017).

5.7.3 Train

Trains are the third mode that this research is taking into account for hinterland transportation of hydrogen (or hydrogen carriers). Similarly to pipelines and barges, trains have the disadvantage of not being very flexible. To transport liquids by train, different rail tankers are required. Rail tankers carrying LH_2 do not exist yet, but they are assumed to be similar to LNG train tankers, ammonia rail tankers are already in use, while oil rail tankers are assumed to be used for the transport of LOHC-DBT (Abrahamse, 2021).

5.7.4 Truck

Trucks are the easiest and most flexible mode of transport of cargo to the hinterland. All three investigated carriers can be transported to the end-user via trucks. In the US, and in different areas of Europe like the Netherlands (Linde, 2020), there are already trucks carrying liquid hydrogen: they are super-insulated, cryogenic tanker trucks (Office of Energy Efficiency and Renewable Energy, 2019). The advantage of carrying liquid hydrogen instead of gaseous hydrogen lies in the fact that much more kgs of hydrogen can be transported by one truck.

Ammonia trucks are used worldwide, usually for short distances of less than 150 km (Elishav et al., 2020). Lastly, LOHC-DBT transport via trucks is not happening at the moment but there are no barriers to transporting it using conventional oil trucks. Therefore, distribution to the hinterland using trucks can be an option for all three of the investigated carriers.

5.7.5 The investigated locations' characteristics

1. Vlissingen

The port of Vlissingen is part of North Sea Port. It is located in the province of Zeeland in the Netherlands, close to the border with Belgium. North Sea Port has put the aim of becoming a hydrogen hub as one of its key targets for the next years (North Sea Port, 2021a). It is important to note, that in the plans of Gasunie for a hydrogen backbone, meaning a hydrogen pipeline system connecting different areas in the Netherlands, with each other and the rest of Europe, there is a plan for a hydrogen pipeline getting to Zeeland (Gasunie, 2020). If this project materializes, then Vlissingen can become a major player in hydrogen import supply chains due to its connection to the end-users. Regarding inland waterway transport, Vlissingen is among others connected to the ports of Terneuzen and Ghent (through the Terneuzen locks), all being part of the same port authority, North Sea Port, and the port of Antwerp. Therefore, there is an extensive network and a lot of possibilities for the transport of hydrogen (or hydrogen carriers) using barges. Vlissingen is connected to main highways and it is close to the industrial areas of North Sea Port and the Port of Antwerp, and it also has a good rail connection that gets inside the terminal of VOPAK.

Liquid Hydrogen Terminal: A liquid hydrogen terminal in Vlissingen, either in a centralized or de-centralized supply chain, has several advantages in terms of hinterland connections. If the hydrogen backbone project becomes reality then the area will be connected to all the industrial clusters of the Netherlands and northern Germany. The port provides a good connection to highways for truck transport, rail transport and barges, which are all relevant when it comes to liquid hydrogen. Thus, a score of "++" is given.

Ammonia Terminal: An ammonia terminal in Vlissingen, next to the existing LPG VOPAK Terminal, would also have significant advantages in terms of hinterland connections. Thus, a score of "+" is given.

LOHC-DBT Terminal: In the possibility of a LOHC-DBT Terminal development in Vlissingen, the connection to the hinterland can also be considered of high prospects. In the case of a centralized supply chain (dehydrogenation at the terminal) and assuming that the hydrogen backbone will be constructed, the dehydrogenated gaseous hydrogen could be transported to the hinterland using the pipeline and/or fuel cells. It is also possible to transport the carrier itself to the end-user using all modalities apart from a dedicated LOHC pipeline, which as explained in Part 5.7.1 is not probable to happen. Thus, a score of "+" is given.

2. Eemshaven

The port of Eemshaven is part of Groningen Seaports, the port authority responsible for the ports of Delfzijl and Eemshaven. It is located in the province of Groningen in the north of the Netherlands, close to the border with Germany. Groningen Seaports have a clear focus on hydrogen. The port, similarly to Vlissingen, is included in the plans of the Hydrogen Backbone. Connection to a nationwide (or even transnational) hydrogen grid could boost the prospects of a liquid hydrogen terminal. Liquid hydrogen can be easily and cost-effectively re-gasified and fed into the grid. A similar process could theoretically work for ammonia or a DBT terminal, with hydrogen being dehydrogenated at the port and then transported to the hinterland through the grid. Regarding the other three transport modalities: the port of Eemshaven is suitable for inland water transport, has a rail connection and easy connection for trucks.

Liquid Hydrogen Terminal: A liquid hydrogen terminal in Eemshaven, especially in the centralized case where the terminal is connected to a hydrogen grid has significant advantages. The port provides a good connection to highways for truck transport, rail transport and barges, which are all relevant when it comes to liquid hydrogen. Thus, a score of "++" is given.

Ammonia Terminal: An ammonia terminal in Eemshaven has significant advantages. In the case of a decentralized ammonia supply chain, transport to the hinterland must be done with trucks, rail transport and inland water transport. Ammonia trucks are usually used in short distances (less than 150 km), while most end-use locations are further than 150 km away from Eemshaven. For the above reasons, a score of "+" is given.

LOHC-DBT Terminal: Similarly to a DBT terminal in Vlissingen, a DBT terminal in Eemshaven can have high prospects as three modalities (truck, rail and barges) are suitable for DBT and the port of Eemshaven is favourable for all three. Transport to the hinterland via pipeline can be done in cases of a centralized DBT supply chain and assuming that the hydrogen backbone will be indeed constructed. Therefore, a score of "+" is given to this alternative.

3. Rotterdam

The Port of Rotterdam is the biggest port in Europe. It is located in the region of South Holland in the Netherlands and starts from the city of Rotterdam itself ending in the coast of the North Sea. A very big part of its cargo is transported to the hinterland via barges, through the extensive network of inland waterways of the Netherlands, Belgium and Germany. The Hydrogen Backbone referred above, if constructed, will be connected to the port of Rotterdam and its industrial cluster. The port also has good connections with highways for trucks. Rail transport from the Port of Rotterdam is possible and a usual mode of transport. However, the rail terminals in the Port of Rotterdam are well connected with other countries but are often congested.

Liquid Hydrogen Terminal: A liquid hydrogen terminal in Maavlakte 2, especially in the centralized case where the terminal is connected to a hydrogen grid has significant advantages. The port also provides a good connection to highways for truck transport, rail transport and barges, which are all relevant when it comes to liquid hydrogen. Thus, a score of "++" is given.

Ammonia Terminal: An ammonia terminal in the Port of Rotterdam, close to the existing LNG Gate Terminal, would also have significant advantages in terms of hinterland connections. Thus, a score of "++" is given.

LOHC-DBT Terminal: Similarly to a DBT terminal in Vlissingen and Eemshaven, a DBT terminal in Rotterdam can have high prospects as three modalities (truck, rail and barges) are suitable for DBT and the port of Rotterdam is favourable for all three. Transport to the hinterland via pipeline can be done in cases of a centralized DBT supply chain and assuming that the hydrogen backbone will be indeed constructed. Therefore, a score of "+" is given to this alternative.

5.8 Other parameters to take into account

Certain aspects related to the planning of a hydrogen terminal were decided to not be taken into account in the MCA, but to be addressed separately in this section. This is due to the fact that they can be a no-go for a terminal investment and are difficult to be quantified based on the four-scale system method that is developed as part of this study. It was considered important to briefly address them for the sake of completeness, but it should be made clear that they are not addressed as part of the developed multi-criteria decision-making methodology.

5.8.1 Geopolitical aspects

Geopolitical uncertainties related to hydrogen projects and supply chains is a topic elaborated in the work of Straatsma, (2021). A decision for a hydrogen supply chain development between alternatives in different countries may entail geopolitical aspects as well. This can be a result of political tensions between the country of export and the one where import is planned. It is expected that green hydrogen production will lead to vastly different power relations than the ones currently existing in the energy system, due to the countries where hydrogen will be produced (Scholten et al., 2020). Pipelines always connect fixed points while ships provide bigger flexibility to the supply chains. The big advantage of hydrogen terminals is that they can diversify their suppliers if tensions arise.

5.8.2 Proximity to urban areas and Public Perception

Safety zones are always an important factor when deciding the location of high-risk infrastructure like a hydrogen terminal. Thus, once a preferred alternative is determined among the investigated ones, it is important to calculate its distance to the closest urban area. A Quantitative Risk Assessment (QRA) is a way to quantify the risks related to terminal operations. The method is successfully used for nuclear and chemical plants (Pasman & Reniers, 2014) for many decades now and can therefore be suitable for hydrogen-related infrastructure. A QRA is however out of the scope of this study and the Multi-Criteria Analysis explained in this chapter. The author recommends to anyone using the developed method, to perform a QRA before progressing to a more detailed design phase. This can verify if the closest urban area is sufficiently far from the terminal location based on the identified risks.

At the same time, public perception is also important when making an investment decision. There are various examples where the disagreement of the local communities led to delays or even cancelling of projects, even if the QRAs showed that no extra risks for the local communities existed. Especially for the oil and gas industry where safety and environmental aspects are always a topic of discussion, public opinion can be crucial (Theodori et al., 2010). When it comes to hydrogen, even some years ago the public opinion was very positive, however, the possibility of even a small decrease in safety due to the switch to hydrogen was considered a key deterrent (Zachariah-Wolff & Hemmes, 2006). In order to consider everyone's opinion, the author recommends organising workshops where the safety measures are taken will be explained and the people will be able to ask questions and express their possible concerns.

6 Case Study

This chapter is examining the application of the two methods developed in Chapters 4 and 5 in the VOPAK Terminal Vlissingen in North Sea Port. First, the case will be explained along with a brief introduction to case studies in general. Afterwards, an assumption for an import scenario will be done. Using openTISim the terminal will be simulated first for a case of a given demand and no limitation in space, and then for a given terminal boundary. Lastly, taking into account the output of the model, the MCA method developed in Chapter 5 of this study the preferred hydrogen carrier will be determined. This Chapter is aiming at answering sub-question E.

6.1 Introduction

In Section 1.4 describing the research methodology an introduction to case studies is provided. The case study is a research strategy in which the researcher tries to gain a profound and full insight into one or several objects or processes that are confined in time and space (Verschuren & Doorewaard, 2010). Throughout the years it has been proved that models and rational analysis may miss certain nuance and context. Thus, case studies are important so as to understand different phenomena based on experience and not only abstract analysis. They provide opportunities to use conceptual tools in authentic activities and wrestle with real problems, allowing engineers to understand the problem in greater detail (Yadav, 2014).

In the current research, an existing liquid bulk terminal will be used as a case study. This is the VOPAK Terminal in Vlissingen, Netherlands. The way that the comparison between them will be done is explained below. The terminal design tool that is developed as part of this research (Chapter 4) will also be applied to the aforementioned case study. Using data from the existing VOPAK terminal site, the terminal layout will be produced to be sure that the design tool is working properly. However, since actual hydrogen import terminals of this scale do not exist it is difficult to compare the output of the tool with an actual project. Data from VOPAK will be acquired regarding the current situation of the studied terminal, the available land close to it and any other data required and which is possible to be provided.

6.2 VOPAK Vlissingen

After a site visit at the VOPAK terminal in Vlissingen that took place on the 27th of May 2021, and desk research to gather information online, the following can be noted regarding the current status and the future plans of the terminal:

- VOPAK Vlissingen is an LPG terminal, with a storage capacity of about 180,000 m^3 divided between three types of tanks (Mounded bullets, Refrigerated tanks, Spheres). A small amount of other chemical gasses is also handled.
- The terminal has four jetties: two for seagoing vessels and two for barges. A maximum draught of 13.5 m is available.
- In the terminal as it is today, there is an available area of about 2.1 ha, see Figure below. The yellow and blue hatched parts as a whole represent the terminal as of today. The blue part is available for new services, for example, a new hydrogen-related service.

- A large area available for a concession is located west of the existing terminal (shown with a blue outline). This area is about 10.8 ha. The terminal manager has stated that if an investment decision is taken this area will probably be part of the expansion.
- The two areas add up to a total of 12.9 ha which is a significant amount of space. This area will be taken into account later when using the terminal design tool integrated into openTISim, as an example.
- According to the terminal manager, the terminal due to its position and abundance of area around it is very promising for hydrogen applications.

Figure 6-1: VOPAK terminal Vlissingen (retrieved from Google Earth and modified by the author)

6.3 Demand Scenario definition

Liquid bulk terminals around the world are of different sizes, strategies and services. For this research the investigated hydrogen terminal scale, strategy and elements have to be defined. This will be based both on a review of relevant hydrogen import terminal studies and on reasonable assumptions.

In general liquid bulk terminals are equipped to handle cargoes in liquid and/or gaseous form. Cargoes that are handled in liquid bulk terminals around the world include crude oil, oil products such as diesel, LNG and LPG. These products are shipped by oil tankers, chemical tankers, parcel tankers and gas carriers (Notteboom et al., 2020). The yard of a liquid bulk terminal usually contains mainly tank storage facilities along with other technical installations such as pump stations. It is very common for liquid terminals to be directly connected by pipelines to a chemical or petrochemical production facility or with national and international grids.

In the case of a hydrogen import terminal, the components of the terminal will vary based on the carrier with which hydrogen will be imported. Given that hydrogen is a very new market it is expected that the first hydrogen terminals will be vertically integrated terminals. This implies that a specified schedule of incoming vessels will exist, serving a specific route between an export terminal (e.g. in Chile or Morocco) and the hydrogen import terminal in the Netherlands. According to a report published by the Port of Rotterdam Authority, an import of about 2 MT of hydrogen is projected for 2035, climbing up to 20 MT in 2050 (Port of Rotterdam, 2020). In the following table, the tonnes of import for LH_2 and the equivalent if the import is conducted using ammonia or DBT as a carrier is shown.

Hydrogen Carrier	Tonnes of imported carrier in 2035	Tonnes of imported carrier in 2050
Liquid Hydrogen	2,000,000	20,000,000
Ammonia	11,350,000	113,500,000
LOHC-DBT	32,100,000	321,000,000

Table 6-1: Projected imports per hydrogen carrier in 2035 and 2050 in the Netherlands

Looking at the numbers in the above table it is clear that very large investments in terminal and conversion infrastructure will be required in the near future. If one takes into account the fact that Rotterdam is a port that is already congested and where not a lot of land is still available for new developments, it can be assumed that a part of the expected imports via Rotterdam will happen via North Sea Port. Based on the total amount of imported hydrogen and the market share of the hydrogen terminal that will be developed the throughput of this terminal can be determined. This is a very uncertain and sensitive assumption as it largely depends on how many companies will invest in the hydrogen economy, how the competition between the two (and other ports in the area) will evolve etc. Thus a bandwidth is used to show the margins of the expected cargo through the hydrogen import terminal to be modelled. A minimum of 5% of the market share and a maximum of 10% are chosen. Based on this assumption, the following table is acquired, which depicts the imported cargo in tonnes that can be expected through the terminal. For the calculations in the following Section, the conservative session will be presented (5% market share). It is also assumed that after 2035 the demand is instantly increased to the 2050 one, and remains constant later on.

Hydrogen Carrier	Share of the total import	Tonnes of imported carrier in 2035	Tonnes of imported carrier in 2050
Liquid Hydrogen		100,000 - 200,000	1,000,000 – 2,000,000
Ammonia	5 - 10 %	567,500 – 1,135,000	5,675,000 – 11,350,000
LOHC-DBT		1,605,000 – 3,210,000	16,050,000 – 32,100,000

Table 6-2: Projects imports per hydrogen carrier in 2035 and 2050 through the investigated import terminal

The lifecycle is assumed to be 25 years, from 2025 to 2050.

6.4 Area required – Terminal Capacity

The input to be used in the simulation are based on the two previous sections. The supply chain along with the annual hydrogen demand are defined in Section 6.3 while the terminal shape and dimension to be used in the area-limited case are elaborated in Section 6.2. For the cost of the lease of land -which is elaborated in Part 4.3.1 of this study- the relevant value for North Sea Port is used.

6.4.1 No area limitation

Firstly, openTISim is used to gain insights on the general case where no limit exists and to determine the required terminal area for the predefined demand scenario. The construction of the terminal is assumed to start in 2025, getting in operation in 2027. After the increase of the demand to 1,000,000 tn per year, the area is not increased again until 2050. For practical reasons of clarity of the graph, all the years are not included.

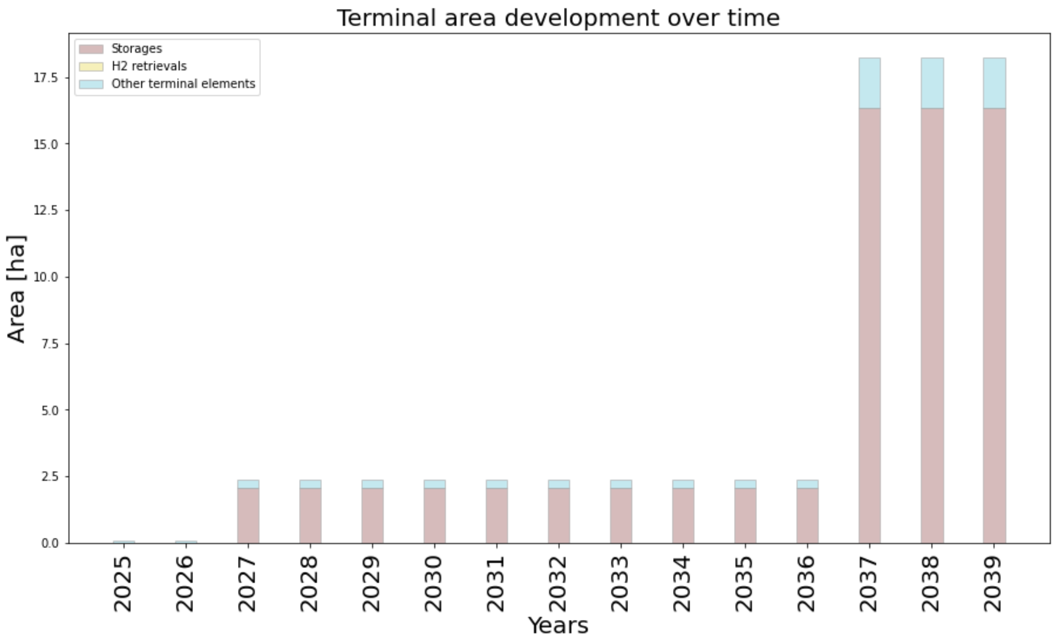

Figure 6-2: Required area for an NH_3 terminal, per terminal element

For the maximum demand of 1,000,000 tn per year, a comparison between the area required for the storage of each carrier is provided. One can see that in 2026 the required area for LH_2 is larger than that of NH_3, something that changes in 2027. This is related to the way the model works: equally-sized tanks are added every time the storage capacity is insufficient. This means that even if the capacity is surpassed by the demand by some tonnes a new tank is added. This leads one tank which is basically underutilized, for example in the LH_2 case until 2026. This can be “fixed” if more tank sizes are added to the model in the future.

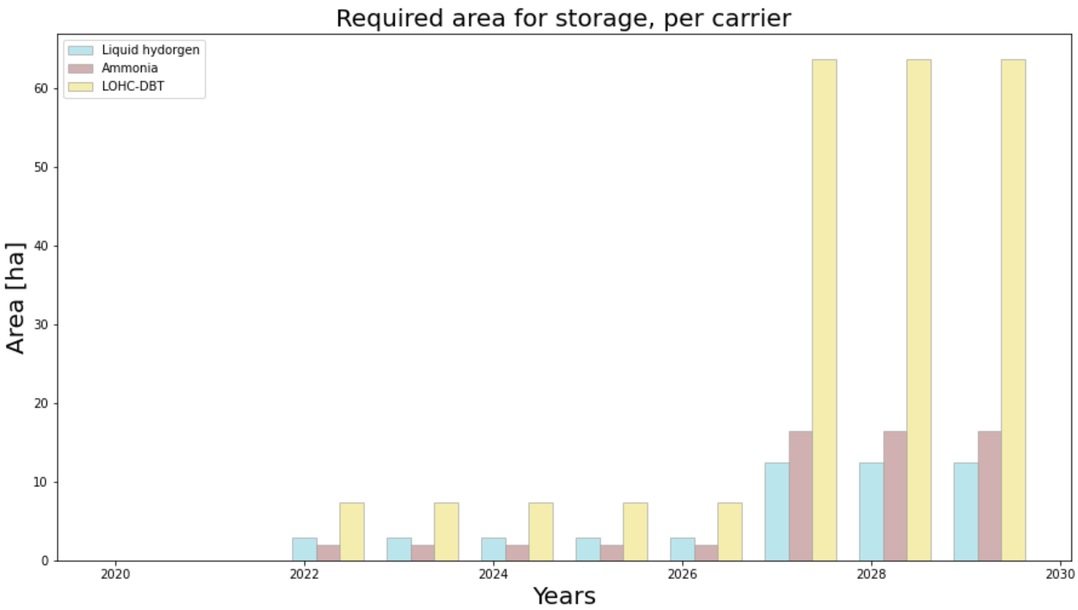

Figure 6-3: Comparison between required area for storage of LH2, NH3 and LOHC-DBT

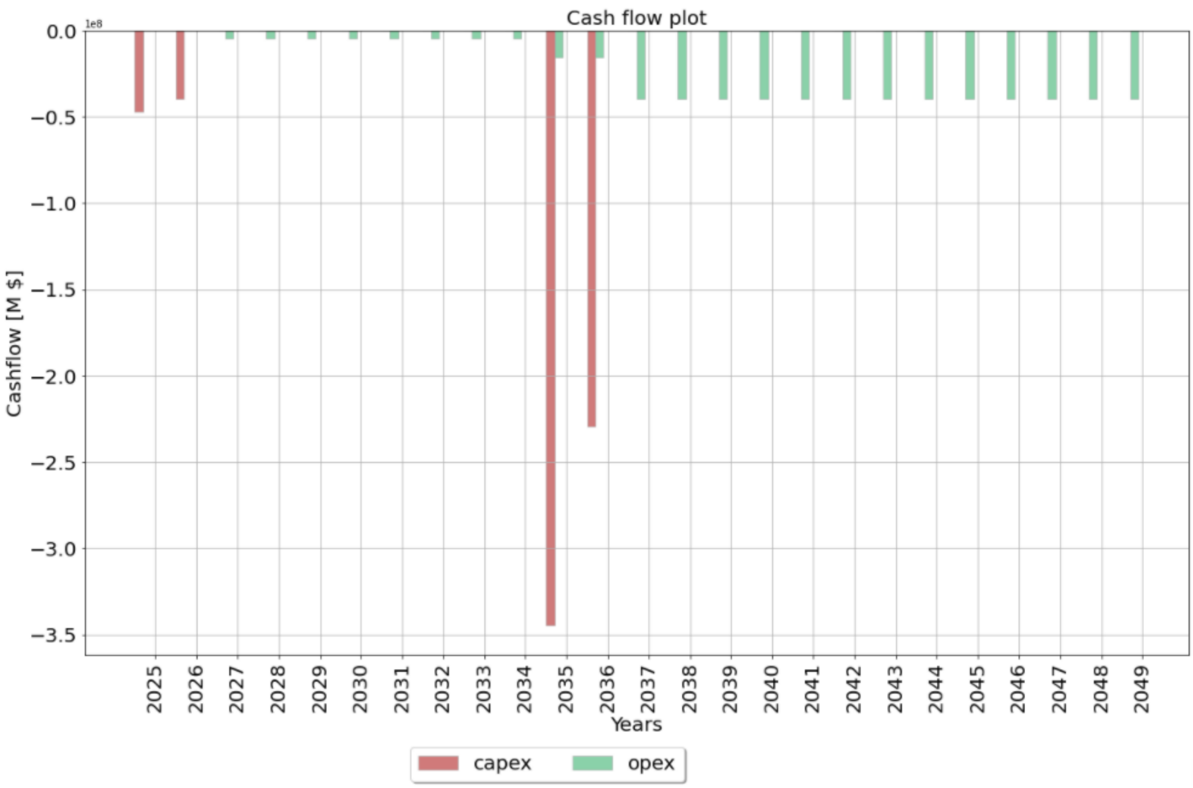

Figure 6-4: CAPEX and OPEX cash flows

One can see that the big CAPEX expenditure appears in the years where the demand increases, while OPEX is doubled after the expansion. The cost of the lease of land defined for North Sea Port in Table 4-3 is used (6 €/m^2/year). In the following table, the operational expenses for the years after 2037 are shown. The cost of the lease of land is about 3.2% of the total OPEX, so a small percentage of the total.

OPEX		
Type of cost	Cost	% of total OPEX
Maintenance	6,562,600	19.5
Insurance	6,562,600	19.5
Energy costs	12,120,000	35.9
Labour	7,387,600	21.9
Cost of lease of land	**1,090,000**	**3.2**
Total OPEX	33,722,800	100.0

Table 6-3: OPEX breakdown NH_3 terminal Vlissingen

In terms of cost per kg of H_2, the cost of the lease of land is about 1,000,000 € for 1,000,000 tn of H_2. Thus, the cost for the lease of land is insignificant for the total cost per kg of H_2, about 0.001 €/kg of H_2. In the case of a DBT terminal, that number can get as high as 0.005 €/kg of H_2 which is still minimal, taking into account that the total cost of the hydrogen supply chain is in the order of 3-5 €/kg of H_2.

6.4.2 Area limitation

In this part of the study, the demand that the given terminal boundary can handle per hydrogen carrier is determined. In Figure 6-5 shown below, the coordinates of the terminal boundary are presented. Those are converted from a WSG84 coordinate system to a custom system at which the point [X,Y] = [0,0] is assumed to be the point of the terminal which is on the bottom left corner.

# of point	X	Y
1	0.0	0.0
2	240.0	0.0
3	240.0	178.9
4	344.4	178.9
5	344.4	382.0
6	240.0	382.0
7	244.0	449.9
8	0.0	449.8

Figure 6-5: VOPAK Terminal Vlissingen expansion coordinates and Google Earth preview of the area

Hydrogen Carrier	Storage tanks	Demand that the terminal can handle [tonnes]	Sufficient remaining space for other elements	Percent of area utilization
Liquid Hydrogen – LH_2	20	765,900	Yes	79.1%
Ammonia – NH_3	11	726,300	Yes	72.1%
LOHC - DBT	4	93,500	Yes	51.3%

Table 6-4: Hydrogen demand that the terminal can handle, per carrier

Looking at Figure 6-6 below, the way the terminal is filled in each case can be seen (left to right: LH_2, NH_3, DBT). It is evident that the DBT terminal visualization is unrealistic as it leads to only four tanks in a non-realistic shape. This can be improved by updating and optimizing the method, to incorporate rectangular storage blocks or two tank sizes. A further elaboration on way to refine this is presented in Section 7.1 – Discussion. In all cases, there is sufficient remaining space for the other terminal elements.

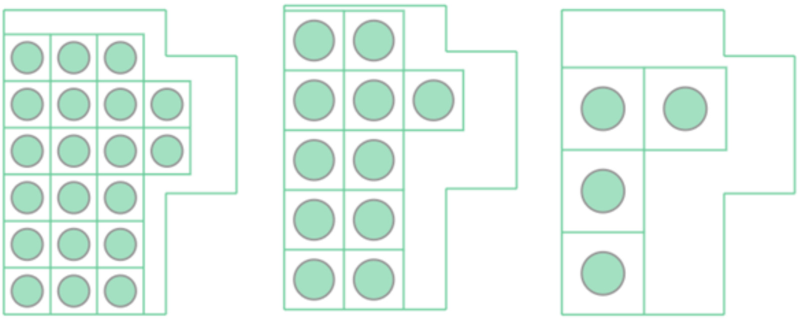

Figure 6-6: VOPAK Vlissingen (all three carriers)

6.5 MCA - Preferred hydrogen carrier

In the Multi-Criteria Analysis method developed as part of Chapter 5, nine criteria are taken into consideration. Criterion 10, related to the technology of dehydrogenation, is not taken into account as a decentralized supply chain is assumed. As a result, minor differences between the score presented in Chapter 5 and the below table can be observed. The VOPAK terminal in Vlissingen is a part of the analysis conducted there as the first three of the nine alternatives were V.LH2, V.NH3 and V.DBT: Namely the options of constructing a liquid hydrogen, ammonia and LOHC-DBT terminal respectively, next to the existing VOPAK terminal in Vlissingen. Thus, the scoring for this case study is already explained. In Table 6-5 below the scoring per criterion and per hydrogen carrier is summarized and the preferred carrier is determined.

#	Criterion	V.LH2	V.NH3	V.DBT
1	Use of existing infrastructure	-	+	--
2	Relationship of the new service to the existing service	+	+	--
3	Carrier Safety	-	--	++
4	Readiness level of the Port Authority in terms of nautical safety	--	++	+
5	Hinterland Connections	++	+	+
6	Proximity to end-users and partnerships	+	++	+
7	Land Availability and Requirement	++	++	+
8	Draft limitations	++	++	--
9	Technology Readiness Level (TRL) of carrier's storage	+	++	++
Score		**5+**	**11+**	**3+**

Table 6-5: MCA - VOPAK Terminal Vlissingen

As can be seen in the case of Vlissingen, a LOHC-DBT terminal is the least favourable case. Liquid hydrogen and ammonia terminals both score well, with a much better score for an ammonia terminal. As a result, the author advises VOPAK to consider this case for further study, hence a preliminary design of a terminal. In the ammonia case, it is assumed that the terminal is handling ammonia which is either used as a fuel or feedstock itself or decomposed at the end-user using small scale ammonia decomposition plants so as to utilize hydrogen. No ammonia decomposition plants are constructed in the terminal itself. Ammonia also has the advantage of a large fertilizer industry present in the area. On the other hand, the implementation of the hydrogen backbone and a hydrogen pipeline could boost the prospects of an LH_2 terminal.

6.6 Final remarks

An ammonia import terminal in Vlissingen, with a decentralized[6] supply chain, is a realistic option even for the coming years. It provides flexibility as ammonia can be utilized as a fuel or fertilizer itself and/or decomposed at the end-user's location. In addition, no technological barriers exist as ammonia transport and storage is fully developed. The terminal has a sufficient depth to accommodate ammonia vessels and has enough space next to it. Ammonia vessels are also already present in the area and no bottlenecks as a result of safety regulations can be expected.

[6] A decentralized supply chain implies that the dehydrogenation does NOT happen at the import terminal, and that the imported carrier is transported to the end use location.

7 Discussion

This chapter includes a discussion of the results of this study. Precious insights gained: from the literature review and interviews on safety issues, from the developed method on hydrogen terminal area calculations and the multi-criteria analysis method are discussed in the first Section. The limitations of the proposed methods are also examined to address the correspondence of them with a realistic case.

7.1 Discussion

With the hydrogen economy in its infancy, ports around the world will face challenges related to the energy transition. In this study, some of those are investigated and insights have been gained on how to address them.

The absence of regulations designed specifically for vessels carrying hydrogen in bulk (LH_2 vessels), as well as the challenges that ammonia tankers bring about, were discussed with experts from four port authorities in the Netherlands. These are: North Sea Port, Port of Rotterdam, Port of Amsterdam and Groningen Seaports. The answers to a common questionnaire revealed that none of the four has finalized rules related to the transport of hydrogen. However, in all four cases, different actions are taken that lead to this direction. The Port of Rotterdam Authority is the one that expressed the greatest confidence that it can handle hydrogen vessels soon. Many of the people that were interviewed expressed the opinion that LH_2 vessels will be treated in the same manner as LNG vessels with some possible extra measures at the beginning. A discussion regarding locks and hydrogen or ammonia tankers was also scheduled with the competent authorities of three locks: the Panama Canal Authority, operating the locks in the Panama Canal, and the Port of Amsterdam which operates the locks of Ijmuiden and RWS which operates the locks in Terneuzen. Again, the opinion of all parties is that hydrogen vessels will pass through locks soon, taking into account the risks that those cargoes involve. Ammonia tankers which are often present in the locks of Terneuzen can serve as an example of how to treat high-risk cargo, especially for the Netherlands.

The calculation of the required area of a hydrogen terminal based on a given demand for all three carriers provided interesting observations. First of all, especially for LH_2 terminals, the safety distances of large-scale LH_2 tanks are not yet regulated. For the choice of an input value to the model, two main factors were taken into account: existing values for small-scale applications and inter distances of already constructed LNG tank farms. The above led to the choice of D/2 as a sufficient value of the distance between two LH_2 tanks. For ammonia tank farms, PGS12 was used, which provides a distance of D/2 and at least 25 m between two ammonia tanks. Lastly, for the LOHC-DBT case, a dominant factor is the containment area. It was assumed that each tank needs a bund wall that can contain its cargo. Using openTISim and based on the number of elements for a given demand the required terminal area is determined. For example, a hydrogen terminal with a yearly throughput of 500,000 tons of H_2 needs 7 LH_2 tanks, or 8 NH_3 tanks or 24 LOHC-DBT tanks, assuming that the supply chain is decentralized. Translating those numbers to areas and considering other terminal elements as well, the total area required is about 7 ha in the LH_2 and NH_3 case, and 36 ha in the LOHC-DBT case (see Figure 7-1). It is therefore evident that the first two require much less space, compared to a LOHC-DBT terminal. This is a result related to both the low hydrogen density of DBT, and the fact that both the hydrogenated and dehydrogenated cargoes have to be stored.

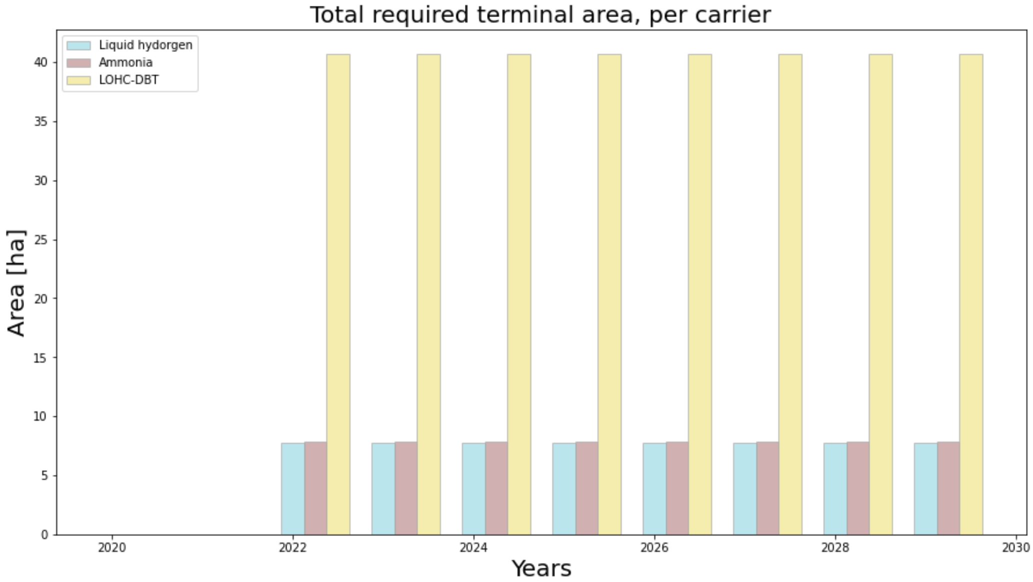

Figure 7-1: Total area required for an annual demand of 500,000 tons of H_2

For a given terminal boundary, the model can provide a first estimate of the capacity that can be handled. This can be done for all three carriers. Simultaneously, a first impression of how the terminal can look like can be produced. Taking a rectangular area of 800x500 m (=40 ha) as an example case, and assuming a decentralized supply chain the following visualizations are produced by the model, one for each carrier (see Figure 7-2). Based on the number of tanks in each case, the average annual capacity of each case can be determined. The LH_2 terminal can handle about 5,000,000 tons of H_2 annually, the NH_3 terminal can handle 2,900,000 tons of H_2 annually, and the DBT terminal can handle only 510,000 tons of H_2 per year. This number is an indication of the average annual capacity. However, for a case where seasonality or other peak factors can play a role, this number should only act as a first estimate (see Part 4.4.2).

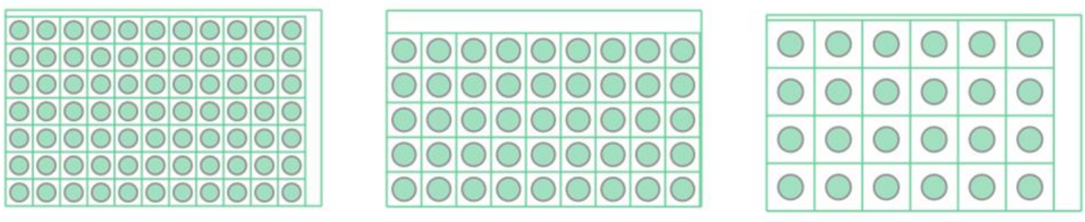

Figure 7-2: Example terminal visualization for all three carriers

Lastly, investigating decision-making aspects for hydrogen terminals, revealed the complexity of such a choice. Even without looking at the problem from a financial perspective which is out of the scope of this study, there are countless other factors that should be taken into account. The multi-criteria analysis method that was developed is specifically tailored for terminals next to existing liquid bulk ones. The relationship between the new and old cargo along with the possibility to use the existing infrastructure in the future is taken into consideration. Applying the method and comparing three port locations where VOPAK is already present, showed that in Vlissingen an ammonia terminal would be the preferred alternative, in Eemshaven a DBT terminal, while in the Port of Rotterdam a liquid hydrogen terminal and a DBT terminal should be investigated. The option of constructing an ammonia terminal next to the existing LPG terminal in Vlissingen scored the highest out of all the alternatives. The capacity of this terminal was also determined using the design tool. An ammonia terminal in Vlissingen and assuming that the available space next to the terminal is 12.8 ha (see Chapter 6) can accommodate approximately 726,300 tn of H_2 per year.

7.2 Limitations of the developed methods

The limitations of this study are presented below. Both the area calculation and design tool model and the multi-criteria analysis method are addressed. This way, the possibilities for further studies can be understood in a better way, and more importantly, the reliability and accuracy of the outputs can be assessed.

1. Model Inputs

The inputs given to the model in order to calculate the required area are based on assumptions and predefined values. For example, for the size of the storage tanks and the capacity of the H_2-retrieval plants the default values of openTISim were used. Those values have to be evaluated further to validate their accuracy. Furthermore, the input value for the area required for an ammonia decomposition plant has not been defined. The author's efforts to do so proved unsuccessful, as explained in Part 4.5.1. Large-scale ammonia decomposition plants are in the development phase and are expected to be constructed soon, but the area required for such a plant is not known at the moment. This limits the applications of ammonia terminals only to decentralized supply chains. A realistic input value can be retrieved via further research or cooperation with the industry. Lastly, other input values like tank inter distances for a liquid hydrogen terminal are based on assumptions, as defined rules for such a terminal do not exist.

2. Element placement method

The way the storage blocks and H_2-retrieval blocks, are placed in a given terminal boundary is not ideal. As also explained before, the method for the area calculations is providing a first, crude estimation. It is limited to one tank and H_2-retrieval size, and the blocks produced are squares. However, the method is very flexible and can be optimized, but at the moment often leads to unrealistic results. For example, a small terminal boundary, where a DBT terminal with a centralized supply chain is to be visualized can lead to results like the figure below. Only one tank and one H_2-retrieval plant "fit" in the given boundary. Also, the capacity of the H_2-retrieval plant is much larger than that of one tank. The solution could be to re-examine the size of the retrieval plant and possibly also the size of the tank. Smaller block sizes can lead to more realistic results.

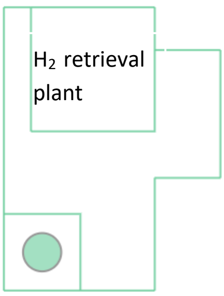

Figure 7-3: DBT terminal example (centralized supply chain)

3. Multi-criteria analysis method

The method developed as part of Chapter 5, is designed to compare alternatives of hydrogen terminals next to existing liquid bulk terminals. A greenfield project of a hydrogen, ammonia or DBT terminal is not its focus. However, if the first two criteria which are related to the existing terminal are dropped, all the other eight criteria are relevant for a greenfield project as well. Some further investigation may need to be done, to determine if aspects relevant for a greenfield project are missing in the current form of the method.

8 Conclusions and Recommendations

This chapter aims at summarizing all the answers provided to the research question and sub-questions in the previous chapters. Section 8.3 entails recommendations that the author makes for further studies, based on all the above.

8.1 Sub-questions

First, all five sub-questions are answered, leading to the answer of the main research question in the following Section.

8.1.1 Investigated hydrogen carriers

The first sub-question aimed at understanding the basic properties, advantages and disadvantages of the three hydrogen carriers that were included in the scope of this study, and is the following:

"What are the properties of the studied hydrogen carriers, what is the state of the art technology regarding those carriers, and what advantages and disadvantages does each one have?"

To answer this question, an extensive literature review on the advantages, disadvantages, properties and technological challenges related to the three carriers was conducted. At first, certain properties like the hydrogen and energy density, and the flammability limits were summarized (Table 2-1). It can be concluded that the three carriers have very different physical and chemical properties. For example, the required storage conditions of each of them are very different: LH_2 at -253°C, NH_3 at -33°C, while DBT can be stored in ambient conditions. Comparisons between LH_2 and LNG, and diesel with DBT were also done (Tables Table 2-2 andTable 2-3). The similarities and differences of those two "pairs" can be easily seen: LH_2 and LNG both need to be stored in low temperatures, they are very flammable and can be easily re-gasified and utilized. Their main difference is their energy density. Diesel and DBT can be stored in ambient conditions, and have a similar density. Same as the previous comparison, however, the energy density of diesel is much higher, more than five times that of DBT. A glance at the latest technological developments for the storage and decomposition of all three (LH_2, NH_3 and LOHC-DBT) along with considerations for their safety, provided insights on their advantages and disadvantages, which were compiled in Table 2-4: H_2-carriers' advantages and disadvantages.

8.1.2 Nautical safety

The second sub-question which aimed at getting insights into nautical safety inside the port environment is the following:

"How do different port authorities approach nautical safety of hydrogen (or hydrogen carriers) in a port environment, and what are the limitations (if any) in the possibility of a hydrogen vessel sailing through a lock?"

This question was approached at a high level and using interviews. Four different ports in the Netherlands were interviewed, along with three other competent authorities. The approaches and goals of all interviewed stakeholders seemed to be in line, with some being a bit ahead of the others when it comes to hydrogen regulations, but without significant differences. Some port authorities are undergoing studies regarding the safety of new energy carriers, others on the safety of new bunker fuels etc. Regarding hydrogen (and ammonia) vessels sailing through a lock chamber, the situation according to the interviewees is pretty clear: the strictest measures will be followed, but hydrogen vessels will be allowed sooner or later to pass through many locks around the globe without significant limitations.

8.1.3 Area calculations and terminal visualization

The next sub-question aimed at developing a method to calculate the area required for a hydrogen terminal for a given demand, or for a given terminal boundary produces a visualization and determine the amount of hydrogen that it can handle, and is given below:

"How can the required terminal area for a certain carrier be calculated, taking into account safety and technical aspects, for a given throughput or the other way around? (calculate the throughput that a certain area can accommodate). What will a conceptual design of such a terminal look like?"

A method was developed to calculate the required terminal area as an answer to this question. The method is based on the number of elements that the existing openTISim can determine for a given carrier and demand. For every tank constructed, its footprint is calculated based on the size of the tank and the required safety area around it. The volume of the tank and the tank type were used to calculate an approximate tank diameter. For the H_2-retrieval plants, based on their capacity, which was pre-existent in the default values of the model, the footprint had to be calculated. For liquid hydrogen and DBT, this was successful, while for ammonia decomposition plants, a representative value was not found despite the efforts and research of the author (see Part 4.5.1). Lastly, other terminal elements like offices, roads and pumping stations were also considered.

Similarly, the throughput that a certain terminal boundary can accommodate can be calculated by the model. A simple method of placing elements next to each other, until the element to be placed is partly outside of the terminal boundary has been developed. When no more elements can be placed the terminal is considered full, and based on the number of elements the capacity is determined. An extra check is conducted to make sure that the remaining space is sufficient for the other terminal elements. This part enables the calculation of the capacity of a given boundary and produces a first visual representation of the terminal.

8.1.4 Multi-Criteria analysis

Sub-question four, aimed at developing a method that can compare different alternative options for an import terminal investment decision and is as follows:

"Using a method of comparison (to be defined or developed as part of this research), determine which of the investigated alternatives would be the most attractive to develop and for which type of activity. Which indicators can be used in order to compare the alternatives and how can they be quantified?"

To answer this sub-question, a method had to be chosen or developed along with the criteria to be taken into account. Ten different criteria were identified by the author which include -among others- the available draft and area at the port location investigated and the safety of the carrier, the readiness level of the port authority. After discussions with PCR experts, it was decided to develop a multi-criteria analysis method with a four scale scoring system. In other words, each of the identified criteria can be scored with --, -, + or ++. An elaborate explanation of how each of the ten criteria can be quantified is also provided as a reference for future use of the method. In cooperation with a major terminal operator (VOPAK) a realistic application of the method was conducted. Three different ports in the Netherlands where VOPAK already has a terminal were identified. For each of those, three options are considered based on the hydrogen carriers that are in the scope of this study leading to nine alternatives. For several criteria, the knowledge acquired based on the previous sub-questions, proved to be vital. The method was then applied to those alternatives providing a first indication of which of those are the most attractive to study further: an ammonia terminal in Vlissingen, a DBT terminal in Eemshaven seem favourable. For the latter however, the limited draft of the port may hinder large tankers to berth. When it comes to the Port of Rotterdam, a liquid hydrogen terminal in Maasvlakte 2 has a good score with a DBT terminal in Botlek being equally interesting.

8.1.5 Case study

The last sub-question is referred to a case study, where the model and the multi-criteria decision-making method will be used, and is as follows:

"Based on the method of comparison, and using the model developed, what would the preferred carrier be for the investigated case study and how will a conceptual design of the terminal look like?"

The case study that both the above methods are applied is an expansion of the existing LPG terminal in Vlissingen owned by VOPAK in order to add a new hydrogen related service. Firstly, using openTISim the required area for a certain demand was determined, along with the cash flows of CAPEX and OPEX. The capacity that the terminal can handle was calculated afterwards, for all three carriers, assuming a given terminal boundary. This boundary was based on the discussions done with VOPAK and the terminal manager during a site visit in Vlissingen. The three carriers were then compared using the MCA method that was elaborated in the previous sub-question, leading to the preferred alternative which is ammonia. Some final remarks regarding ammonia in Vlissingen were also included to provide a holistic approach to this possibility.

8.2 Main research question

Taking into account the answers to all of the sub-questions, the main research question of this study can be addressed. The question as defined in Chapter 1, is the following:

"How can hydrogen (or a hydrogen carrier) be integrated as a new service in an operational port environment, and next to an existing liquid bulk terminal?"

For all the three investigated hydrogen carriers (LH_2, NH_3 and LOHC-DBT) the regulations in the port environment are missing, but they do not seem to be a showstopper for a hydrogen import terminal in the Netherlands. Especially for NH_3 and DBT, the situation is simpler as ammonia supply chains exist, and DBT does not require extra or stricter regulations than a typical oil tanker. Even for LH_2 Dutch ports seem ready to follow at a fast pace as long as investments start emerging. At the same time, the development of a hydrogen terminal will require new space, and as shown in this research, much more space than existing fossil fuel terminals. Especially in the case of DBT the area required is much larger than the other two carriers and in ports with limited space like the Port of Rotterdam, retrofitting oil infrastructure may be necessary. Lastly, the research conducted when developing a multi-criteria analysis method for this study showed that a lot of questions remain when it comes to choosing a preferred alternative. The developed method can provide a first indication to terminal operators and decision-makers, on which alternatives to study further, develop business cases and explore their opportunities. All the above, answer some of the challenges (those that are in the scope of this study) on how to integrate hydrogen in an operational port environment, next to existing liquid bulk terminals and provide the framework for further research on this topic.

8.3 Recommendations

This research focused on hydrogen import terminals, and further investigated three key aspects: nautical safety during transport to the terminal, terminal layout design and area requirements, and investment decision making for hydrogen terminals. It is evident that the hydrogen port sector is not yet developed and thus there is a lot of space for research something that also becomes clear in this study. This section provides some recommendations for further research, mainly based on what the author came across during this study:

- The regulations regarding both nautical and terminal safety are not yet present. Port authorities claim that a first investment is required to conduct all the relevant studies, while some players in the market seem discouraged by the absence of a stable safety framework. A study focusing on a quantitative risk assessment (QRA) related to hydrogen and ammonia vessels in a port environment (and through lock chambers) could provide precious insights. The same applies to a QRA of the tank inter distances, and the proximity of a terminal to urban areas.
- The model used for calculating the required terminal area, and to produce a schematization of a hydrogen terminal is openTISim. The input values (tank inter distances, H2-retrieval plants' dimensions etc.) have to be updated when new information becomes available, as some of the parameters are based on crude estimations. Especially for ammonia and LOHC-DBT de-hydrogenation, big advancements in technology will be crucial and provide input values with much better accuracy. Research related to large scale plants of ammonia decomposition and LOHC-DBT dehydrogenation is therefore recommended.
- The degree of optimization of the terminal layout can also be improved by further studies. This study focused on creating a basis for a conceptual design, while others could take into account much more factors and details in order to produce a relatively realistic result. Examples can be the exact layout of pipelines inside the terminal and buildings or other obstacles around the terminal that may influence the layout due to the existence of safety distances between those and the hydrogen terminal infrastructure. In addition, the method is very flexible and can produce more realistic results in various ways. One could be to introduce two storage tank sizes: this would mean that if the "big storage tank" cannot fit, the model would check if the "small storage tank" can fit. An increased terminal capacity can be expected as the total terminal area will be utilized more optimally. Another option can be to not limit the storage blocks to squares, but give the option for rectangular shapes as well, while always keeping the safety distances in mind, while more terminal elements (pipelines,

offices etc) could also be added to the design with some extra work and design rules. In general, the method gives countless opportunities for further optimization due to its flexibility and simple way of thinking.

- The multi-criteria analysis method developed can be updated, using more criteria and an even more objective quantification framework. In addition, the method can be tweaked to be suitable for pure greenfield projects as well.
- During this study, the author communicated with different stakeholders of the hydrogen supply chain. A common question for many was the possible social concerns of new technologies like Liquid Hydrogen and Ammonia. Studies and polls to investigate those questions could provide valuable insights to decision-makers and if problems arise, take the required measures to inform the public and decrease any safety concerns.

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Appendix A – LOHCs comparison

In the following table, a comparison between LOHCs can be seen. The three compared carriers are:

1. Dibenzyltoluene (DBT), a very promising LOHC that is very safe and easy to handle. The hydrogenation and de-hydrogenation of DBT are commercialized by a company in Germany called Hydrogenious.
2. Methylcyclohexane (MCH), one of the first LOHCs that have been studied in the past decades. MCH has the advantage of being at the level of an almost mature technology when it comes to hydrogenation and de-hydrogenation.
3. Methanol, which is a well-known chemical. Its biggest advantage is that it is already being traded and handled on many sites worldwide. However, the fact that it requires CO_2 upstream of its supply chain is a significant disadvantage.

In the table below, the LOHCs are compared taking into account different aspects. Their energy density and efficiency of their de-hydrogenation process, their Technology Readiness Level (TRL), the possible use of existing infrastructure and/or vessels, their feedstock cost based on the literature, their NFPA 704 safety diamond and the possible impact on aquatic life in case of a LOHC spill. Certain challenges that need to be overcome before they can be used on a large scale are also highlighted. It must be noted, that for the cost, the material cost for the production of each LOHC can be seen, excluding the price of hydrogen.

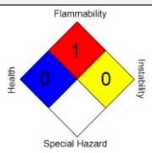
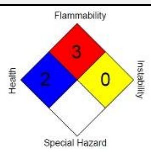
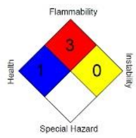
Aspect of comparison	DBT	MCH	Methanol	Unit
Energy density	6840	5692	11870	[MJ/m³ LOHC]
Losses due to de-hydrogenation	About 20 % if heat is available nearby	About 30 %	-	[%]
TRL	6-7	7-8	9	[-]
Use of existing infrastructure	Possible	Possible to an extent	Methanol infrastructure already exist	[-]
Feedstock cost	3.5 €/kg	0.6 €/kg	About 2 €/kg	[€/kg H_2]
Safety and Hazards (according to NFPA 704)				[-]
Environmental assessment	Toxic to aquatic life with long-lasting effects (H411)	Toxic to aquatic life with long-lasting effects (H411)	Low toxicity to aquatic life	[-]
Biggest challenge	Heat required to improve its de-hydrogenation cost	Volatile and highly flammable	CO_2 required upstream	[-]

Table A-1: Comparison of LOHCs based on various aspects

Methanol is generally considered as a fuel or hydrogen carrier that could significantly cut greenhouse emissions (Methanol Institute, 2019), however, it is still not entirely "clean" and thus it will not be considered a part of this study. Regarding the comparison between DBT and MCH, it is evident that the two LOHC's are very similar. In terms of energy density, MCH contains about 83% of the energy of DBT. The biggest difference lies in the fact that DBT is extremely easy to handle and store, while MCH is a highly flammable and dangerous cargo. At the same time, the importance of available heat nearby of the de-hydrogenation plant is vital in both cases in order to decrease the energy losses. Due to the fact that this study is paying attention to safety aspects with DBT being the less flammable and dangerous of the two and that one of the biggest companies that are investigating and producing DBT hydrogenation and de-hydrogenation plants is a partner of VOPAK, DBT is chosen to represent the wide range of LOHC's in this study. It should be noted, however, that both MCH and methanol are considered very promising -mainly due to their low production costs- and therefore many studies are focusing on them.

Appendix B – Questionnaire and answers regarding locks

The questionnaire included 6 main questions to start the discussion. In certain cases, aspects not referred in the questionnaire were discussed. The 6 questions are the following:

1. Are there any existing rules/regulations regarding liquid hydrogen vessels?
2. If not, what would happen if a vessel carrying hydrogen in bulk was to pass through the locks? Would a decision be made based on a case-by-case approach? Would such a transit possibly be rejected or accepted?
3. Is the Port Authority planning to develop safety requirements for a liquid hydrogen vessel? Or wait for other competent authorities and then apply those?
4. What is the procedure if a new type of cargo that need special treatment in terms of safety is introduced? How long may such kind of rules need in order to be implemented?
5. What is the experience from similar cargoes in the past? How were the LNG rules introduced?
6. What extra measures exist for LNG vessels for example, or other cargo that require special treatment in terms or safety, compared to other vessels? Do such kind of vessels have e.g. priority in the queue for safety reasons? Are there any special measures/rules worth having in mind?

Interview 1: Confidential Source related to the Panama Canal Authority

Note that not all questions from the above questionnaire were addressed as it was an informal confidential communication.

1. *There are no extra regulations at the moment.*
2. *There is no inquiry by such a vessel until today, but theoretically, there should not be any bottleneck whatsoever provided that: [1] vessel is compliant with international and Panama Canal maritime safety and transit regulations, [2] the vessel has timely booked and paid the toll fees for the transit, regardless of the route.*
3. *Please note that Panama Canal maritime regulations for navigation in Canal Waters are duly cross-referenced to most current international codes and regulations (including but not limited to IMO). Thus, each and every vessel (including but not limited to hydrogen gas carriers, if any) requesting transit shall comply with relevant international and Panama Canal maritime safety regulations (including but not limited to IMO).*

Interview 2: RWS – Interviewee Maciel Noijen, Strategic Advisor and Peter Alkema, Strategic Policy Advisor and Project Manager / 22-06-2021

Note that the locks in IJmuiden are owned by RWS but operated by the PoA.

1. *Regulations exist for various cargo, including ammonia but hydrogen not part of those at the moment. Those specify if two ships are allowed at the same time in the lock chamber.*
2. -
3. *The Port Authority is in close cooperation with RWS and other stakeholders involved but risk analysis studies are yet to be conducted.*
4. –
5. *At the moment no LNG vessels pass through the locks of IJmuiden. Hypothetically, hydrogen vessels would definitely be alone in the lock chamber but no priority can be expected.*
6. -

Interview 3: Port – Interviewee Rudi Adam, Nautical Advisor Terneuzen Locks / 22-06-2021

Note that the locks in Terneuzen are both owned and operated by RWS.

1. *No regulations at the moment in Terneuzen regarding hydrogen. In general, despite the fact that inland transport is well regulated in the Netherlands, sea-going vessels' rules follow international rules and guidelines.*
2. *In the case of a hydrogen vessel probably a similar procedure will be followed with the one followed for ammonia vessels that pass through the locks. Either way, the rules applying to ammonia vessels at the moment are as strict as they can get and will be sufficient for hydrogen vessels. What extra could we do for hydrogen vessels? Probably nothing…*
3. *RWS is in close cooperation with NSP and other stakeholders involved.*
4. *-*
5. *-*
6. *No LNG vessels pass through the locks apart from barges. Ammonia vessels however are locked separately, and a specific/detailed plan for their trip from the pilot station to the berth is determined prior to their arrival. No priority.*

Extras: Public perception of the risks related to both ammonia and hydrogen is extremely important. Ammonia however may in the end be much more dangerous.

Appendix C – Questionnaire and answers regarding nautical safety

The questionnaire included 6 main questions to start the discussion. In certain cases, aspects not referred in the questionnaire were discussed. The 6 questions are the following:

1. Are there any existing rules/regulations regarding the nautical safety of vessels carrying liquid hydrogen to a terminal?
2. If not, what would happen if a vessel carrying hydrogen in bulk wanted to enter the port? How would the port approach it in terms of safety?
3. Is the (Port) Authority planning to develop safety requirements for a liquid hydrogen vessel? Or wait for national and international regulations?
4. What is the procedure if a new type of cargo that need special treatment in terms of safety is introduced? How long may such kind of rules need in order to be implemented?
5. What is the experience from similar cargoes in the past? How were the LNG rules introduced?
6. What extra measures exist for LNG vessels for example, or other cargo that require special treatment in terms of safety? Do such kind of vessels have e.g. no waiting time in the anchorage, bigger distances from other vessels or urban areas? Are there any special measures/rules worth having in mind?

Interview 1: North Sea Port - Interviewee Jean-Pierre Maas, Nautical Advisor NSP / 04-06-2021

1. *There are no additional rules for hydrogen yet because we do not yet have this in the port. On the other hand, these will differ little from the existing regulations from IBC, IGC and ADN.*
2. *The first run is always exciting in the sense of it being new and unknown. North Sea Port has the advantage that ships first have to navigate the Western Scheldt, where the GNA is the BA. The GNA will carefully study the entry and contact us. Usually, there will also be contact with the VRZ. Together we will then determine a policy. It will be something that ships should not have any delay on the river and should be able to sail straight on and moor at the desired berth. Visibility should be at least 2000 m. If not the vessel may need to wait at an anchorage until the weather conditions are acceptable.*
3. *We are not currently working on this. In view of the developments, this could happen, but it is not yet entirely clear to me what shipload we can/will receive.*
4. *Is a different/special treatment required for hydrogen? Of course, it is new and of course, a lot of attention will be paid to it and of course, many parties want to have something to say about this.*
5. *We don't really have LNG as cargo in the port, but we do as bunkers. In principle, bunkers/fuels are not subject to regulations such as IBC, IGC and ADN. Bunker ships must apply for a permit from the Harbor Master for the supply of LNG. The rule that we now apply is that if they have a sea permit in, for example, Antwerp or Rotterdam, they also obtain it for North Sea Port. We use the same audit.*
6. *Directly to the berth, visibility at least 2000 m? During the entire journey (pilot berth). Distance is regulated in, among others, BPR and SRKGT.*

Interview 2: GNA - Interviewee Vivian Baetens, GNA Nautical Advisor / 17-06-2021

Note: Mr Dan de Bruijn, from Veiligheidsregio Zeeland was also present in the meeting

1. *No regulations exist at the moment, specifically tailored to hydrogen but GNA is working on developing such rules.*
2. *If it was decided along with the Ports and Fire Brigade that is it safe for a vessel to enter.*
3. *Yes, GNA is working on it, trying to gather all required information in order to develop its own rules. GNA is an authority where two countries (Belgium and the Netherlands) are represented, thus good cooperation is required. Generally, the authority is in good cooperation with NSP, Port of Antwerp and Veiligheidsregio Zeeland.*
4. *Both Belgian and Dutch sides should sign any rules that will be officially implemented, thus it can take up to a year for the whole procedure. However, if any investment is to happen the authority along with the port of interest will know it beforehand so it will have time to do whatever is necessary.*
5. *As said above the rules were introduced after cooperating with all stakeholders involved. There is no LNG cargo, but only bunkering at the moment.*
6. *Bunkering of LNG vessels allowed, in specified places when the sea-going vessel is anchored.*

Interview 3: Port of Rotterdam - Interviewees Cees Boon, Senior Safety Advisor PoR / 11-06-2021, and Wim Hoebee, Manager Nautical Affairs and Projects PoR / 17-06-2021

1. *We performed a nautical risk study (HAZID) that included 5 example locations in different areas of the port. We concluded the present safety framework for vessels with Dangerous Goods in our port is sufficient for the expected growth of vessels carrying the new energy carriers. In case an investment is decided the next steps would be a real-time nautical simulation and a dynamic mooring analysis.*
2. *A vessel compliant with SOLAS and MARPOL is allowed to enter the port based on International legislation. An off-standard vessel or vessel in distress is only allowed to enter our port under strict conditions.*
3. *Locally we will adapt the regulations (Port Bye Laws). We are involved in the regulatory processes within national and international regulatory authorities to make sure they will not overlook the port perspective in new regulations.*
4. *Present safety framework for activities with DG on board of vessels or in the interface between vessels and shore is for a large part sufficient. Some extra items will be adapted.*
   Hydrogen vessels don't need special treatment, We will handle them as every other vessel with DG on board.
5. *The admission policy for LNG tankers was developed after some nautical studies and collision studies. In our nautical HAZID, we concluded the results of these studies for LNG can also be used for tankers with other "new" energy carriers as cargo. All risk mitigation is focused on avoiding crossing courses.*
6. *All risk mitigation is focused on avoiding crossing courses. At the start, there were some extra precautions. Pilots have to get used to the behaviour of large LNG carriers. Now the approach to the Nile- and Yukon haven is a regular activity, the admission rules are minimized. The same process will be used for the new cargoes, and then when experience is gained the measures can be relaxed.*

Interview 4: Port of Amsterdam - Interviewee Maciel Noijen, Strategic Policy Advisor and Peter Alkema, Strategic Policy Advisor and Project Manager / 22-6-2021

1. *Right now, no specific rules regarding hydrogen vessels exist. In 2011 a study related to the safety of* LNG *carriers in the port was conducted. This was done due to the possibility of a medium-scale* LNG *terminal investment. This included ship to ship* LNG *transport.*

2. –
3. *The PoA is looking into hydrogen -both for production in the area and for import- at a commercial stage at the moment. No study regarding vessels carrying hydrogen in bulk is conducted until now. However, a study related to marine fuels that included LNG and new fuels like hydrogen, methanol and ammonia is finalized but not yet published. The main conclusion is the existing framework is sufficient for all of those except ammonia, where because of its toxicity further research is needed.*
4. *In the case of an investment decision, the Port Authority would need a time period of maximum a year (still a crude estimate) to conduct the related safety studies. No limitations can be expected.*
5. –
6. –

Extras: The PoA is in close cooperation with all stakeholders to make sure that when rules will be developed all the safety aspects will be taken into account. In addition, both interviewees noted the importance of public opinion especially for the Port of Amsterdam which is located close to urban areas.

Interview 5: Groningen Seaports - Geert-Jan Reinders, Dept. Harbourmaster / 19-7-2021

1. *No hydrogen-related regulations exist at the moment.*
2. *React according to circumstances and probably in cooperation with Port of Rotterdam*
3. *Yes on the first. The Port Authority is talking to all involved stakeholders including the Port of Amsterdam and Port of Rotterdam authorities.*
4. –
5. *Long period of time to prepare for this. Harmonisation of procedures etc. with Rotterdam and Amsterdam (we do not want to compete on safety).*
6. *Sea our port by-laws, to be found on our website.*

Appendix D – Hand calculation example

In this Appendix, a validation of the area calculations and graphs produced by the developed model is performed, by doing a hand calculation of the processes. The number of elements as calculated by openTISim is assumed as input in the case where no area limitation exists, while the terminal shape and dimension is the input in the area-limited case. In the following table, the input parameters as provided to the model are summarized. This table is identical to Table 4-4 but is included here for practical reasons.

Terminal Element	Feature	LH_2	NH_3	LOHC - DBT
Storage Tank	Type of tank [-]	Spherical	Cylindrical double-walled	Cylindrical with dome roof
	Capacity [tn]	3,550	34,130	52,850
	Capacity [m^3]	50,350	51,000	58,000
	Diameter [m]	**46**	**59**	**63**
	Height [m]	**46**	**18.5**	**19**
	Tank inter distance [m]	**D/2**	**D/2 or 25 m**	**Based on the containment area**
	Bund wall height [m]	**-**	**-**	**4**
H_2 - Retrieval	Type of H_2 - retrieval	LH_2 gasification	Ammonia cracking	DBT de-hydrogenation
	Capacity [tn carrier/day]	3,288	-	17,808
	Capacity [tn H_2/day]	3,288	-	1,104
	Area [m^2]	**1,125**	**-**	**38,800**
	Dimensions [m x m]	**45 x 25**	**-**	**197 x 197**
Other terminal elements	**Area for offices, parking [m^2]**	**5,000**	**5,000**	**5,000**
	Area for pumping stations [m^2]	**2,000**	**2,000**	**2,000**
	Area for things directly related to the terminal's size (space for roads, pipelines etc)	**10 % of the total**	**10 % of the total**	**10 % of the total**

Table E-1: openTISim inputs

Storage Block area:

Based on the input of the above Table the storage block for each carrier is calculated.

- For LH_2 the inter distance between two tanks is defined as equal to D/2 (half a diameter). This implies that each 'storage block' will be 1.5D x 1.5D = 2.25D^2 m^2 and taking into account that D = 46 m, storage block area = 2.25*46^2 = 4,761 m^2 per storage tank.
- For NH_3 the inter distances is again defined as equal to D/2 or at least 25m. This leads to a storage block area = min[(1.5D x 1.5D), (D+25 x D+25)] = min[2.25D^2, (D+25)^2] = min[2.25*59^2, (59+25)^2] = 7,832 m^2 per storage tank
- For DBT the storage block is defined based on the containment area. The bund wall to be located around each tank should be able to contain the total volume of each

tank. Based on the total volume of the tank, the volume of the tank that is above the bund wall height must be determined as this is the one that has to be contained.

Volume to contain $= \pi * (D/2)^2 *$ *(tank height – bund wall height)* $= 46{,}759\ m^3$

Using the above value the required dimension of the storage block can be determined as follows:

(storage block dimension)^2 * *bund wall height = volume to contain* + $\pi D^2/4$ * *bund wall height => storage block dimension = 121.7 m*

Carrier	Storage block dimension (m)	Storage block area (m^2)
Liquid Hydrogen – LH_2	69	4,761
Ammonia – NH_3	88.5	7,832
LOHC – DBT	121.7	14,641

Table E-2: Storage block sizes

H2-retrieval Block area:

For the retrieval blocks for the re-gasification of liquid hydrogen and the dehydrogenation of LOHC-DBT, the areas and dimensions are as presented in Table E-1.

No area limitation example

To calculate the required terminal area for a given demand, the number of elements required is used as input. The model calculates if extra elements are required based on the demand of each year. In other words, if the storage tanks in line are not sufficient to cover the demand, the model adds new ones. For this example, a constant (throughout the years) hydrogen demand of **1,000,000 tons per year is assumed**, and the supply chain is assumed to be decentralized. The number of elements per carrier for a certain year of the simulation is shown in the table below (the numbers are acquired via the pre-existing openTISim functions). With the number of elements now known and based on the input presented above, the area calculation can be executed. An example for the LH_2 terminal is shown in Table H-4.

Type of element	Amount of elements	Area (m^2)	Total terminal area (m^2)
Storages	26	26 x 4,761 = 123,786	147,818
H_2 – retrievals	2	2 x 1,125 = 2,250	
Offices and pumping station	-	7,000	
Other elements	-	14,782 (= 10% of the total)	

Table E-3: LH_2 terminal calculations

The required terminal area is equal to 14,78 ha. The above-acquired number corresponds to the area provided by the model, as can be seen in the print screen below:

```
The total area required is: 14.781777777777776 ha
```

Similar examples can be executed for (decentralized) ammonia terminals and DBT terminals.

Area limited example

In this example, the input is the terminal's shape and dimensions, and the output is the demand that this given boundary can accommodate. The model fills the terminal with elements until there is no more space available. Special caution is given to always keep the capacity of the H_2-retrievals higher than the total capacity of the storage tank. This means that a retrieval plant is added every time that the capacity of the storages reaches a certain limit. The terminal boundary to be used as input for this example is a rectangular terminal with dimensions 800 x 500 m. The model will provide the number of elements that can fit in this terminal and based on that, the capacity of this terminal will be determined.

According to openTISim, the above defined terminal boundary can accommodate:

- 77 liquid hydrogen tanks
- 45 ammonia tanks
- 24 DBT tanks

Based on the above the yearly averaged demand that those tanks can handle will be calculated, taking into account losses due to boil-off, dwell time and buffer. Using the equations as explained by Abrahamse, (2021) in her study the opposite calculation, having the number of tanks as given, and the terminal capacity as the unknown can be conducted:

$$Storage_{cap\ dwell} = number\ of\ tanks * tonnes\ per\ tank$$

$$Max\ storage\ capacity = Storage_{cap\ dwell} / (1.1 * allowable\ dwell\ time)$$

$$Max\ storage\ capacity\ (in\ H_2) = Max\ storage\ capacity\ /\ H_2\ content$$

$$Maximum\ capacity\ (at\ the\ jetty) = (1 + Losses) * Max\ storage\ capacity\ (in\ H_2)$$

The following table shows the calculations, for each carrier.

From number of tanks to maximum capacity			
	LH2	NH3	DBT
Number of tanks	57	11	4
Tonnes per tank	3525	34130	52850
Storage_cap dwell = number of tanks X tonnes per tank	200925	375430	211400
Days for dwell	30	30	45
Losses_storage / day	0.06	0.03	0
Losses (as % of the total cargo)	1.8	0.9	0
Buffer	1.1	1.1	1.1
H2 content %	100	17.65	6
Max storage capacity (as carrier)	2,222,352	4,152,483	1,558,808
Max storage capacity (in H2)	2,222,352	732,913	93,528
Maximum Capacity (at the jetty)	**2,183,057**	**726,375**	**93,528**

Table E-4: Maximum terminal capacity for each carrier

The capacity of the LH_2 and NH_3 terminals are almost identical. On the other hand, the capacity of the terminal if the carrier is DBT is five to six times less.

Appendix E – MCA Evaluation Framework

In this Appendix, certain details regarding the evaluation framework of the Multi-Criteria Analysis conducted as part of this research are explained. In the following Table, the indicators that were taken into account along with the elaboration regarding their scores are presented.

Category	Criterion	Score	Explanation	Remarks / Comments / Way of quantification
Operations	**1. Use of existing terminal infrastructure**	++	Existing infrastructure (storage tanks, jetties, pipelines etc) can be used with minor modification.	Based on the literature review and experts consultation.
		+	Existing infrastructure can be used with modifications.	
		-	Existing infrastructure needs major modifications and retrofitting to be usable.	
		--	Existing infrastructure not usable by the new carrier. New infrastructure has to be constructed.	
	2. Relationship of the new service to the existing service	++	Existing terminal cargo is very similar to the carrier to be added.	This indicator is aiming at taking into account the operational difficulties that a completely new cargo could impose to a terminal if added (for example new personnel or training of existing personnel required etc).
		+	Existing terminal cargo is similar to the carrier to be added (for example both refrigerated when stored).	
		-	Existing cargo and new carrier have minor common characteristics.	
		--	Existing cargo and new carrier are not related operations wise.	
Safety	**3. Carrier safety**	++	Carrier is not flammable, not explosive, not toxic to humans.	Carrier specific, based on the Literature Review
		+	Carrier has two of the below characteristics (for example is it flammable but not explosive or toxic).	
		-	Carrier has one of the below characteristics.	
		--	Carrier is flammable, explosive and toxic to humans.	

	4. Readiness level of the Port Authority in terms of nautical safety rules	++	The Port Authority has already developed the framework and conducted the required studies.	Based on interviews with various Port Authorities, but also related to the hydrogen carrier (for example no extra rules are required for DBT if Oil Tankers are already present).
		+	The PA has started studying the nautical safety of hydrogen but rules are not finalized yet.	
		-	The PA has conducted safety studies regarding bunkering but not on bulk transport of hydrogen.	
		--	The PA is gaining information to conduct the relevant studies, but no study has started yet.	
Infrastructure and current Port situation	**5. Hinterland Connections**	++	All four modes of hinterlands transport are available (trucks, train, barges, and pipeline) or concrete plans for execution exist at the port location and are applicable for the given carrier.	Elaborated on Section 5.7
		+	Most modes of transport are present and are applicable for the given carrier.	
		-	Even though most modes of transport are present at the port, most of them are not applicable for the given carrier.	
		--	The port and the carrier both have limited options for the connection to the hinterland	
	6. Proximity to end users and partnerships	++	The port is close or connected to the industry and various hydrogen related projects are excepted to happen.	Guidelines on what to take into account when scoring this criterion are provided in Appendix G.
		+	The port is at an area where hydrogen is expected to play a role in the future.	
		-	The port's location is adequate for hydrogen related investments but no significant end users exist nearby.	
		--	The port's location is not close to possible clients and other hydrogen projects don't seem likely.	
	7. Land availability and requirements	++	Available land next to the existing terminal and carrier area required is less than that of its peers.	Based on the insights of the area calculations, and the land availability next or close to the investigated terminal
		+	Available land next to the existing terminal, but carrier requires significant amount of land.	

		-	Limited available land but carrier does not require more area than other carriers.		
		--	Limited to no available land in the area and carrier requires significant amount of land.		
	8. Limitations due to the available draft	++	The location's draft can accommodate every vessel of the alternative's carrier.	Related to the available draft at the location and the expected draft of vessels of each carrier. For example, DBT import will require big tankers, which need a large draft available at the import terminal.	
		+	The location's draft can accommodate some vessels of the alternative's carrier.		
		-	The location's draft can accommodate a limited amount of vessels of the alternative's carrier.		
		--	The location's draft cannot accommodate most vessels of the alternative's carrier.		
Technology	**9. Technology Readiness of the carrier's storage**	++	TRL (Technology readiness level) of storage is 8/9.	Carrier specific, based on the Literature Review	Definition of TRL's
		+	TRL of storage is 6/7.		
		-	TRL of storage is 4/5.		
		--	TRL of storage is 2/3.		
	10. Technology Readiness of the carrier's H2 - retrieval on a large scale	++	TRL of large scale de-hydrogenation is 8/9.	Carrier specific, based on the Literature Review	
		+	TRL of large scale de-hydrogenation is 6/7.		
		-	TRL of large scale de-hydrogenation is 4/5.		
		--	TRL of large scale de-hydrogenation is 2/3.		

Appendix F – Criteria evaluation

Carrier Specific Criteria:

- <u>Carrier Safety:</u> Taking into account that Liquid Hydrogen is both flammable and explosive, that ammonia is extremely toxic as well as flammable . On the other hand, DBT is hardly flammable and non-explosive and can be toxic if swallowed which is a highly unlikely possibility. Thus, DBT is considered not flammable, not explosive and not toxic to humans. As the criterion is carrier-specific and thus the location is not affecting the score the above are summarized in the following Table (note that in this Table as well as all the following Tables the number given to each one of the criteria is also indicated).

3. Carrier Safety	
Carrier	Score
LH_2	-
NH_3	--
DBT	++

- <u>Technology Readiness Level of Storage:</u> Taking into account the definition of the TRL's as defined by the European Commission, 2014 the maturity of each technology can be assessed. For the storage of ammonia, TRL is assumed to be 9 as there are many ammonia terminals worldwide. For the storage of LH_2, the technology is assumed to be demonstrated in a relevant environment, thus its TRL is assumed to be 6. DBT storage is not carried out on a large scale currently thus it is difficult to say that the technology is mature. However, due to the properties of DBT, no limitations can be expected and therefore TRL of storage of DBT is assumed to be 8.

9. TRL of carrier's storage		
Carrier	TRL	Score
LH_2	6	+
NH_3	9	++
DBT	8	++

- <u>Technology Readiness Level of large scale de-hydrogenation:</u> Taking into account the definition of the TRL's as per European Commission, 2014 the maturity of each de-hydrogenation technology can be assessed. For LH_2 gasification an ORV technology is assumed as explained in Chapter 2. This technology is used worldwide for the gasification of LNG and no barriers are expected for a similar use for LH_2 and for that reason a high TRL is assumed. For ammonia cracking the technology is still at a low level of readiness. A TRL of 4 is assumed. DBT de-hydrogenation is commercialized and thus at a TRL of 9 for small scale applications. According to Hydrogenious, there is no big technological barrier to scale up the technology. Based on those two factors a TRL of 5 is assumed for the de-hydrogenation of DBT on a large scale.

10. TRL of carrier's de-hydrogenation		
Carrier	TRL	Score
LH_2	7	+
NH_3	3	--
DBT	5	-

Other criteria

For all other criteria, the scoring is based on a case by case approach, which means that the criteria are scored independently for each one of the alternatives.

- Use of existing terminal infrastructure: The scoring and explanation of the score of each of the 9 alternatives are presented in the following table.

1. Use of existing terminal infrastructure		
Alternative	**Score**	**Explanation**
V.LH2	-	VOPAK Terminal Vlissingen is primarily an LPG terminal. LPG is stored at -40°C and therefore major modifications would be required in order to store LH_2.
V.NH3	+	NH_3 is stored at - 33°C and thus at a higher temperature than LPG. Also, the fact that NH_3 is heavier than LPG would mean that without conducting any structural modifications, LPG tanks could only be filled with ammonia partially.
V.DBT	--	DBT is a liquid in ambient conditions and much heavier than LPG. Thus the current infrastructure would not be usable by an oily liquid such as DBT.
E.LH2	--	VOPAK Terminal Eemshaven is a crude oil strategic storage terminal. Thus for refrigerated cargo like LH_2 and NH_3 new infrastructure is required.
E.NH3	--	
E.DBT	++	For DBT storage and handling, minor modifications would be sufficient.
R.LH2	-	Based on the assumption that an LH_2 import terminal will be constructed close to the Gate terminal, infrastructure can be used if modified (Kolff, 2021) and retrofitted.
R.NH3	+	Same as above, according to Kolff, 2021, LNG tanks can be used after some modification for the storage of NH_3.
R.DBT	++	Assuming that a DBT terminal in the Port of Rotterdam would be constructed close to an existing oil terminal, existing infrastructure could be used with minor modifications.

- <u>Relationship of the new service to the existing service:</u> This criterion focuses on operational difficulties that terminal personnel would face if a completely new type of cargo was introduced. Differentiations come mainly from the form of each service compared to the existing one (compressed gas, refrigerated gas, or liquid). In this criterion, the risks related to terminal safety are included. This implies that if an alternative scores well in this criterion, then regardless of the safety issues related to the cargo, safety in the terminal itself is assured.

2. Relationship of existing service to new service		
Alternative	**Score**	**Explanation**
V.LH2	+	LPG and LH_2 are both stored in liquid form. Operation wise similar processes are required.
V.NH3	+	The same applies to ammonia and LPG. They are both refrigerated and stored as liquid.
V.DBT	--	DBT is a diesel-like liquid that is stored in ambient conditions, thus very different operationally than LPG.
E.LH2	--	Eemshaven is an oil terminal, and thus it would require completely new personnel and processes so as to run an LH_2 terminal.
E.NH3	--	As said right above, Eemshaven is an oil terminal, and thus it would require completely new personnel and processes so as to run an NH_3 terminal as well.
E.DBT	++	A DBT terminal would be very similar operation wise to the existing terminal, which stores oil and other oil-like liquids.
R.LH2	++	An LNG terminal like the one at the Port of Rotterdam will have a lot of common characteristics operations' wise with an LH_2 terminal.
R.NH3	+	Also for an NH_3 terminal, given the fact that both cargoes are refrigerated when stored and are quite difficult to handle, we assume that the two products do have some common characteristics in terms of operations.
R.DBT	++	A DBT terminal next to an existing oil terminal would mean that the same personnel could handle both products.

- <u>Nautical safety / Readiness of the Port Authority:</u> The score of this criterion is based on the interviews with Port Authorities (see Chapter 3). For LOHC-DBT it is assumed that no extra regulations are required and therefore all three ports are considered to have started working on the relevant rules.

4. Nautical safety / Readiness of the Port Authority		
Alternative	**Score**	**Explanation**
V.LH2	--	The port is gaining information to develop rules and conduct the studies, but no study has started yet.
V.NH3	++	Ammonia vessels are already present in North Sea Port but not in the port of Vlissingen.
V.DBT	+	DBT regulations are similar to oil. Thus, it can be assumed that the PA has started working on such rules, but they are yet to be made official.
E.LH2	--	Groningen Seaports is gaining information in order to develop rules and conduct the studies, but no study has started yet.
E.NH3	+	Ammonia is not present in the port, and thus it is assumed that the port needs extra rules before being able to accommodate ammonia vessels.
E.DBT	+	DBT regulations are similar to oil. Thus, it can be assumed that the PA has started working on such rules, but they are yet to be made official.
R.LH2	+	The port of Rotterdam has started investigating the nautical safety of vessels carrying hydrogen in bulk and a hazard identification study has been conducted. However, the regulations have not been finalized yet.
R.NH3	++	Vessels carrying ammonia in bulk are already present in the Port of Rotterdam.
R.DBT	+	DBT regulations are similar to oil. Thus, it can be assumed that the PA has started working on such rules, but they are yet to be made official.

- Hinterland connections: The scoring for this criterion is elaborated in Section 5.7 of this study and is summarized in the Table below.

5. Hinterland connections	
Alternative	**Score**
V.LH2	++
V.NH3	+
V.DBT	+
E.LH2	++
E.NH3	+
E.DBT	+
R.LH2	++
R.NH3	++
R.DBT	+

- Proximity to end-users and partnerships: During the literature review, the latest developments regarding hydrogen related projects in all three ports were made clear. All the three ports have announced studies, partnerships and coalitions with various stakeholders related to hydrogen (Companies, Institutes, Universities, etc). At the same time, the proximity to end-users is different for each port.. For guidance when it comes to the evaluation of the proximity to end-users and partnerships, the information provided in Appendix G can be considered as a starting point.
  The advantage of the Port of Rotterdam is that it could have some potential clients of hydrogen inside the port itself. It should also be noted that due to the existence of the Yara production facility in North Sea Port, the strategic position of the terminal in Vlissingen for an ammonia terminal is considered better than that of an LH_2 or DBT terminal, due to its proximity to a big ammonia user. The above are summarized in the following Table.

6. Proximity to end users and partnerships		
Alternative	**Score**	**Explanation**
V.LH2	+	An LH2 terminal in Vlissingen would be close to the industrial cluster of the port of Antwerp. North Sea Port is also very active in establishing partnerships.
V.NH3	++	An ammonia terminal in Vlissingen would be close to the Yara production facility and the industrial cluster of the port of Antwerp. North Sea Port is also very active in establishing partnerships.
V.DBT	+	A DBT terminal in Vlissingen would be close to the industrial cluster of the port of Antwerp. North Sea Port is also very active in establishing partnerships.
E.LH2	+	An LH2 terminal in Eemshaven would be close to the industrial cluster of the port of Delfzijl. Groningen Seaports are also very active in establishing hydrogen-related partnerships.
E.NH3	+	An ammonia terminal in Eemshaven would be close to the industrial cluster of the port of Delfzijl. Groningen Seaports are also very active in establishing hydrogen-related partnerships.
E.DBT	+	A DBT terminal in Eemshaven would be close to the industrial cluster of the port of Delfzijl. Groningen Seaports are also very active in establishing hydrogen-related partnerships.
R.LH2	++	The port of Rotterdam is very close to end-users as it has an industrial cluster inside the port itself, while the port authority and various companies are part of coalitions and partnerships for LH2.
R.NH3	++	The port of Rotterdam is very close to end-users as it has an industrial cluster inside the port itself, while the port authority and various companies are part of coalitions and partnerships for NH3.
R.DBT	+	The port of Rotterdam is close to end-users as it has an industrial cluster inside the port itself if a big dehydrogenation plant is constructed in the terminal, while the port authority and various companies are part of coalitions and partnerships for DBT.

- Land availability and Requirement: As explained in Chapter 4 the required land for a DBT terminal is significantly larger (more than double) than the land for a liquid hydrogen of ammonia terminal. Between a liquid hydrogen and an ammonia terminal, the differences are minor and thus a similar area requirement is assumed. Regarding the availability of land in the three investigated ports, both North Sea Port and Groningen Seaports have big areas available for expansion of the existing terminals. On the other hand, the Port of Rotterdam has a very limited area available (on Maasvlakte 2) which is not directly connected to the existing VOPAK terminals. In the Port of Rotterdam, a more viable option would be the conversion of an existing terminal to a hydrogen related one.

7. Land availability and requirement		
Alternative	**Score**	**Explanation**
V.LH2	++	Liquid hydrogen terminals require the least area compared to the other two carriers and there is available land next to the VOPAK terminal in Vlissingen.
V.NH3	++	Ammonia terminals require a similar area to LH2 terminals, and there is available land next to the VOPAK terminal in Vlissingen.
V.DBT	+	DBT terminals require much more space than ammonia and liquid hydrogen, but there is plenty of space available next to the VOPAK terminal in Vlissingen.
E.LH2	++	Liquid hydrogen terminals require the least area compared to the other two carriers and there is available land next to the VOPAK terminal in Eemshaven
E.NH3	++	Ammonia terminals require a similar area to LH2 terminals, and there is available land next to the VOPAK terminal in Eemshaven.
E.DBT	+	DBT terminals require much more space than ammonia and liquid hydrogen, but there is plenty of space available next to the VOPAK terminal in Eemshaven.
R.LH2	-	Liquid hydrogen terminals require the least area compared to the other two carriers but there is very limited available land next to the Gate Terminal.
R.NH3	-	Ammonia terminals require a similar area to LH2 terminals, but there is very limited available land next to the Gate terminal.
R.DBT	--	DBT terminals require much more space than ammonia and liquid hydrogen, and there is very limited to no land available next to the VOPAK Botlek terminal.

- Limitations due to available draft: The scoring for this criterion is based on available data at the sites of VOPAK on the draft available at each location and on the assumed draft per vessel type. In the first table, the available draft per location is shown and in the second one, the draft per vessel type is summarized. The values of the left table are obtained from the default values used by openTISim and are verified, comparing them with data on vessels of each type. For liquid hydrogen vessels, the draft of 'Suiso Frontier' is used as a starting point (about 5 m) (Marine Traffic, 2021) and extra information is obtained from the literature regarding the future trends of hydrogen vessels. However, it is certain that due to hydrogen's low density, LH_2 vessels (similar to LNG vessels) will not have significant drafts. Based on the evaluation framework as explained in Appendix @@, the scoring of each alternative is carried out.

Available draft per location [m]	
Vlissingen	13.5
Eemshaven	11
Rotterdam (GATE)	14
Rotterdam (Europoort)	21

Vessel draft per carrier and vessel type [m]		
LH2	Small hydrogen vessels	10
	Large hydrogen vessels	12
NH3	Small ammonia tankers	9.5
	Large ammonia tankers	11
DBT	Panamax	10
	Handysize	13
	VLCC	18.5

8. Limitations due to available draft		
Alternative	**Score**	**Explanation**
V.LH2	++	All hydrogen tankers can be accommodated.
V.NH3	++	All ammonia tankers can be accommodated.
V.DBT	-	Panamax and Handysize tankers can be accommodated, but DBT transport mainly done by VLCC tankers.
E.LH2	+	Only small hydrogen vessels can be accommodated.
E.NH3	++	All ammonia tankers can be accommodated.
E.DBT	--	Only Panamax tankers can be accommodated, and DBT transport mainly done by VLCC tankers.
R.LH2	++	All hydrogen tankers can be accommodated.
R.NH3	++	All ammonia tankers can be accommodated.
R.DBT	++	All Oil tankers carrying DBT can be accommodated.

Appendix G – Guidelines on the criterion 'Proximity to end users and partnerships'

Below one can find some basic guidelines on how to evaluate a port's position for projects related to hydrogen, concerning the end-users. It must be made clear that this kind of analysis requires a study on itself (something which is outside of the scope of this thesis) and thus the information presented below can only be considered as a starting point for such an evaluation.

Local Hydrogen Demand – Possible clients in the area or good connections with industrial areas:

- If the area close to or around the port is an industrial area where possibilities for hydrogen demand exist, then the terminal is strategically located. Getting into more detail, sectors like iron and steel industry and chemical industry are some examples of likely hydrogen users in the near future (IEA, 2019).
- In addition, if the investigated port is a bunkering port with a lot of traffic of sea-going and/or inland vessels, the prospects of a hydrogen terminal are increased. This especially applies to ammonia, which has substantial potential as a marine fuel (IRENA, 2019). As stated in Chapter 3 of this study, both the ports of Rotterdam and Amsterdam have already started investigating the possibilities of new marine fuels, as well as the corresponding safety aspects related to such a change. According to Herdzik, 2021 ammonia is going to be one of the marine fuels of a 'transition phase' and in about two decades the hydrogen era will emerge at its full extent (Herdzik, 2021). When it comes to LOHCs, efforts are underway to even develop LOHC-fueled ships, as announced in July 2021 by Hydrogenious and Østensjø (Hydrogenious LOHC Maritime AS, 2021). The above imply that ports that already offer bunkering services, have a sizable advantage regarding hydrogen (or hydrogen carriers) investments.
- The existence of fertilizer industry close to or around the port can also be considered a big advantage in the case of an ammonia terminal, due to the importance of ammonia as a feedstock for the fertilizer industry (FAO, 2017).
- Given the prospects of hydrogen as aviation fuel, the existence of an international airport in the area can also be considered beneficial (Siddiqui & Dincer, 2021).
- A connection with big and vital inland waterways that lead to industrial areas far away from the port is also considered a plus.

Partnerships - Other hydrogen related projects:

- It can be expected that the hydrogen economy will develop around hydrogen hubs and clusters (ISPT, 2019). This implies that other hydrogen related projects in the area of the port, like hydrogen production (electrolysis) plants, hydrogen pipelines, pilot projects etc will give an extra boost to the import terminal and thus make its strategic position even better. A list of announced or under development projects in the area can give a good indication of its hydrogen momentum.
- Coalitions, partnerships and/or memorandums of understanding between the Port Authority and other stakeholders related to hydrogen can also create prospects for the port as a whole, and subsequently for the investigated import terminal.

Appendix H – Ammonia Decomposition plant requisition document

The document shown below was sent to Proton Ventures on the 22nd of October 2021.

Graduation Project

"Challenges of integrating hydrogen in an operational port environment"

Serafeim Bachras, MSc student Hydraulic Engineering, Delft University of Technology
in cooperation with Port Consultants Rotterdam

The below information provides a picture of a properly defined situation of an ammonia import terminal. The requested output from Proton Ventures, is an estimation of the footprint of the ammonia decomposition plant, in terms of total area and dimensions.

It should be noted the information is asked for research purposes only, to be used for an MSc thesis. If needed it can be kept confidential when the research will be published.

1. **Terminal Type:** Ammonia Import Terminal
2. **Purpose:** Ammonia is used as a hydrogen carrier, and the supply chain is such that 100% of the imported ammonia is decomposed to H_2 and fed into a hydrogen grid.
3. **Demand:** The terminal to be designed will have an H_2 demand of 200,000 tonnes, to be fed to the grid. This implies about 1,130,000 tonnes of ammonia per year.
4. **Amount of tanks and tank size:** Only one tank size is assumed of about 34,000 tonnes each (50,000 m^3). Assuming a dwell time of 30 days, 4 tanks are required according to my model.
5. **Ammonia Decomposition plant:** The demand of the plant is assumed to be equal to the summation of the end-use demand (1,130,000 tonnes), and the plant losses as shown below:

$$Demand_{Plant\ in} = Demand_{End\ user} + Losses_{Plant}$$

Assuming that the losses account for 1%, the demand of the plant is equal to **1,141,300 tonnes of NH_3. This implies a capacity of about 200 tn NH_3/hour assuming 5840 operational hours per year.** (For this decomposition plant it is assumed that no additional purification step is added to the plant. The purity of the hydrogen for the NH_3 power plant is therefore only suitable for hydrogen that is intended for combustion and not for hydrogen used in fuel cells).

Based on the above information the area and dimensions of the decomposition plant are the requested outputs.

Appendix I – Python Code

This Appendix contains a QR Code that directs to the Github website where the python packages for this code are available.

In the folder 'notebooks' you can find some more examples that give a clear understanding of how the terminal investment simulation works. The folder 'notebook_examples_Bachras_Serafeim' contains the examples that were developed as part of this thesis, and are focused on the area requirements of hydrogen terminals.

Figure J.1: QR leading to the Python packages