Laying the foundation for a hydrogen refueling network for inland cargo ships in the Netherlands and Germany: A roadmap to 2050

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1. INTRODUCTION

A global urgency for switching from fossilized fuel to more sustainable fuel types has emerged. An increasing number of alternative fuel vehicles are being developed and used (Yu, et al., 2021). However, the heavy transport sector is lagging in this transition. The transport sector in Europe is responsible for 25% of the CO2 produced in Europe (European Commission, 2020). It is the only major sector that is continuing to rise in energy usage. Despite the growing energy usage, there are initiatives and there is potential to make the switch to more sustainable fuel types in the heavy transport sector. Examples of initiatives are heavy-duty trucks fueled on hydrogen in China (Lao, et al., 2020) and electric passenger busses in Stockholm (Xylia, et al., 2017).

The transition to more sustainable fuel sources for smaller vehicles has fewer barriers to overcome than for heavy-duty transport, due to heavy-duty transport having more technical constraints and commercial motives that limit the use of alternative fuels (Langshaw, et al., 2020). For heavy-duty vehicles, several steps need to be taken to make the transition to more sustainable fuel types (Forrest, et al., 2020). The two most important steps are to create a larger demand by making heavy-duty alternative fuel vehicles commercially feasible and to create an infrastructure capable of refueling the vehicles.

The first step, to create a larger demand by making alternative fuel vehicles more commercially attractive, is already developing. This demand is expected to increase significantly over the next decades. On one side, the production and storage of sustainable fuel types will become cheaper and more accessible due to technological improvements (Apostolou & Xydis, 2019). Additionally, governmental subsidies are provided to compensate for high initial investments. On the other side, governments will introduce restricting regulations and penalties on emissions in the heavy-duty sector in national and international policies (Ajanovic & Haas, 2018). To avoid making rushed decisions when restricting regulations will be announced, transport companies can already explore opportunities to switch to more sustainable options.

For the second step, to create an infrastructure capable of refueling sustainable fuel types such as hydrogen, several considerations have to be made. The first important consideration is to choose between different refueling options. Hydrogen can be used as fuel in gas form, pressurized gas form, liquid form or bound to other substances. Neither of those options currently are widespread available. At this moment inland cargo vessels can refuel fossilized fuels at nearly all ports (Zhen, et al., 2017). The bunkering of fuel in inland cargo ships is possible in multiple ways, including pipeline-to-ship (PTS), using a bunkering ship, or truck-to-ship (TTS) (Ursavas, et al., 2020). For PTS, a physical refueling location is present. A bunker ship is a rare way of refueling for inland cargo ships. With TTS a truck delivers fuel to the ship. When using hydrogen as fuel, PTS and TTS are the most suitable options (National Renewable Energy Laboratory, 2014).

It is important to note that little research is done on refueling location problems for hydrogen in maritime transport. Therefore, the literature will be observed from a broader perspective, incorporating research on more alternative fuel transport modalities. Refueling locations for maritime transport have distinct factors to take into account. Important factors that differ for ships are lesser mobility, significantly larger tank sizes, and more energy needed than most land transportation modes. For the location of refueling points, it is important to look at port locations, access from large waterways which have fixed routes, and that it is hard for ships to change their route since deviating from routes is difficult.

This research will focus on the future of hydrogen-fueled inland cargo ships. The research question of this study is "How can the transition towards a hydrogen-fueled inland cargo ship network be organized most efficiently?". Since hydrogen refueling stations are expensive and the amount of hydrogen-fueled cargo ships will be relatively low in the next decades, it is not feasible to place a hydrogen refueling location in every inland port the vessels pass. Therefore, it is important to investigate which locations strategically are most efficient. To find answers to this question, the literature will be extensively explored and barriers in the transition will be identified. From the literature, a model will be chosen that suits the problem. The model will be extended to fit this research. Afterwards, a case study based on qualitative and quantitative data will be held. By combining the literature and this research, a roadmap to 2050 will be created in which different necessary steps are described. This research is done in cooperation with a consortium partner, which will be called as Company A in this report.

In the next chapter, the theoretical background will be explored. The third chapter will go in-depth on the methodology used in this research. The fourth chapter elaborates on the case study. In the fifth chapter, the results of the research will be presented. The sixth chapter consists of a discussion of the results and implications for managers. The last chapter contains the conclusion, which will also include the limitations of this study and future research opportunities.

2. THEORETICAL BACKGROUND

In this research, two different aspects of the logistics literature will be explored. These aspects are the refueling facility location problem and the literature regarding hydrogen as a fuel. First, an overview of using hydrogen as a fuel type will be given. Afterwards, a summary of the literature regarding the refueling facility location problem will be given. After that, the technological, economic and, political/legal barriers of using hydrogen as an energy carrier for maritime transport will be identified.

2.1. Hydrogen as fuel

Over the last decades, the search for efficient and sustainable fuel types started due to concerns about natural resources and environmental problems. Hydrogen can play a significant role in the transition to a sustainable energy system by being a zero-carbon energy carrier that can be easily stored and transported (Atilhan, et al., 2021; Staffell, et al., 2019). Hydrogen as a fuel type is especially interesting due to the ability to reach a longer range than electric transport modalities and requiring less weight in energy storage to achieve this range (Morrison, et al., 2018). Hydrogen is used in transport by combining hydrogen with oxygen in fuel cells. The reaction between hydrogen and oxygen produces electricity that can be used in an electric engine. A conversion loss in the fuel cell from hydrogen to energy should be taken into account (Ajanovic & Haas, 2018). For using hydrogen as fuel in the current energy system, there is currently not enough consumer demand to support building a hydrogen refueling network but at the same time, there are not enough refueling stations to justify the purchase of hydrogen-fueled transport modalities. To overcome this problem the public sector can aid by helping with initial investments and giving the hydrogen infrastructure a boost. It is essential to look at the minimum requirements to have a successful initial siting of refueling locations for inland cargo ships.

Hydrogen refueling systems have some specific features that are not always taken into account in other refueling systems. One aspect to take into consideration is the time it takes to refuel hydrogen (Isaac & Saha, 2021). When comparing refueling hydrogen to refueling fossil fuels, it takes approximately the same time, but when comparing it to charging electricity it is significantly faster (Yavuz & Çapar, 2017). Another consideration is that hydrogen refueling systems have the option to make refueling stations self-providing (Pereira Micena, et al., 2020). This can be done by either a solar park or wind turbine nearby. When producing green hydrogen on location, the refueling location becomes more independent, which can be useful when the resource is scarce or difficult to transport. A relatively high conversion loss when electrolyzing the wind or solar energy should be taken into account, compared to using the energy for other purposes (Nikolaidis & Poullikas, 2017). If producing hydrogen on location is not possible, a hydrogen network with either pipelines or refueling trucks is necessary.

In maritime transport, refueling takes place with the bunkering of a fuel type. Cargo ships can refuel at bunkering locations or have fuel ships deliver the fuel from bunkering locations to ships. For inland cargo ships, it is common to refuel at a bunkering location. Bunkering locations get refilled either by land transport of fuel or transport tankers (Peng, et al., 2021). With hydrogen, this is challenging but expected to be possible (Keizer, et al., 2019). Hydrogen in maritime transport can be used as fuel in gas form, pressurized gas form, liquid form, or attached to other substances, such as sodium borohydride, ammonia, or formic acid. For research on the usage of hydrogen as a fuel for ships in the port of Lauwersoog, these different options were compared by Keizer et al. (2019). The comparison was made on different aspects, such as safety, availability, efficiency, and storage costs. From this comparison, hydrogen in pressurized gas form came out as most suitable for maritime applications. Hydrogen in gas form can be pressurized at different hydrogen pressure levels (Lin, et al., 2018). Commonly used pressure amounts are 300-bar, 500-bar, and 700-bar. When hydrogen is pressurized, it is possible to fit more hydrogen in a tank (Parra, et al., 2019). This is especially useful when the size of the fuel tank cannot exceed a certain size. A fuel tank needs to be specially adapted to hold pressurized hydrogen, which comes with increased costs (Keizer, et al., 2019). Refueling with higher pressurized hydrogen leads to ships having more range, at the cost of being more expensive (Lin, et al., 2018). A refueling location that can deliver hydrogen at higher pressure is more expensive to construct and maintain (National Renewable Energy Laboratory, 2014). Figure 1 shows the cost breakdown of a distributed kilogram of compressed hydrogen. Compression is the main driver of the costs. Compression in this breakdown entails compression capital, energy consumption, and maintenance and operations costs. Compressing to a higher pressure increases the costs further. Besides compression, it is also possible to make a distinction between normal and fast-fill refueling stations in hydrogen. Fast-filling stations have a higher capacity but are more expensive than normal filling speed refueling stations.

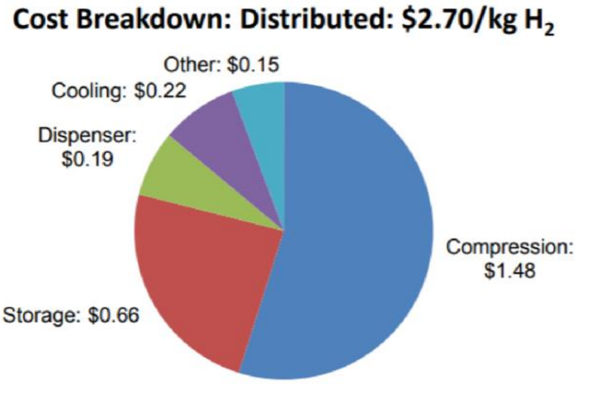

Figure 1: Cost breakdown of 1 kilogram compressed hydrogen (National Renewable Energy Laboratory, 2014)

2.2. Refueling location problem

Emerging sustainable fuel sources, such as hydrogen, cannot function without a functioning infrastructure (Capar, et al., 2013). Refueling locations are an important part of this infrastructure. However, due to the minimal demand and generally high prices of refueling locations for new fuel types, it is not feasible to place refueling locations at many locations. For that reason, a model is needed to place the refueling locations at places where their strategic impact is the highest. The first research on alternative fuel vehicle (AFV) refueling location planning focuses on light-duty vehicles (Kuby & Lim, 2005; Wang & Lin, 2009). In this period it became evident that adequate refueling availability is one of the most important factors of commercializing AFVs (Melaina & Bremson, 2008). More recently, the scope in refueling location problem literature broadened by also incorporating the energy transition of heavy-duty transportation modalities such as trucks, trains, and ships.

Two types of refueling location models are most commonly used in the literature: node-based refueling location models and path-based refueling location models (Honma & Kuby, 2019). In node-based location models, the points of interest are centroids of certain areas, whereas path-based location models use the origins and destinations of routes to find the most relevant points for the placement of new refueling stations.

In Table 1, an overview is provided presenting various important studies in the field of refueling location models. This study is included to illustrate its positioning in the literature. In this table, the studies are categorized based on different characteristics. The first characteristic the studies are categorized on is the modality type in the study. The division is made between light-duty transport modalities (LDM), land-based heavy-duty transport modalities (HDM), and water-based heavy-duty transport modalities (WHDM). The second characteristic on which a distinction is made is the fuel type in the research. When research is done on the global idea of alternative fuels, without specifying the fuel type, this is given in the table as Not Specified (NS). The specific alternative fuel types that have been distinguished are Liquefied Natural Gas (LNG), electricity, and hydrogen. The third and fourth characteristic of the different researches are whether the research developed a node-based or a path-based model and whether this model is linear or nonlinear. The fifth characteristic is a distinction between research with one vehicle class and research with multiple vehicle classes. When working with multiple vehicle classes the model becomes more complex and more realistic, because it is possible to work with different tank sizes and ranges (Hwang, et al., 2017). The last characteristic on which the different researches are distinguished is how the refueling is done. The different options are Pipeline-to-Modality (PTM) and Truck-To-Modality (TTM).

Table 1: Literature table

	Modality type			Fuel type				Model choice		Model Type		Single or multi-class		Refueling options	
Study	LDM	HDM	WHDM	LNG	Electric	Hydrogen	NS	Path	Node	Linear	Nonlinear	Single	Multi	PTM	TTM
Kuby & Lim (2005)	X						X	X		X		X		X	
Kuby & Lim (2010)	X						X	X		X		X		X	
Göpfert & Bock (2019)	X				X			X			X	X		X	
Hwang, Kweon & Ventura (2017)	X	X		X				X		X			X	X	
Jung et al. (2014)	X				X				X		X	X		X	
Kang & Recker (2015)	X					X		X			X	X		X	
Kuby, Capar & Kim (2017)		X		X				X		X		X		X	
Lin & Lin (2018)	X						X	X			X	X		X	
Upchurch & Kuby (2010)	X						X	X	X	X	X	X		X	
Brey et al. (2016)	X						X		X		X	X		X	
Wang & Lin (2009)	X						X	X			X	X		X	
Yildiz, Arslan & Karasan (2016)	X						X	X		X		X		X	
Ursavas, Zhu & Savelsbergh (2020)			X		X			X		X			X	X	X
Smid (2021)			X			X		X		X			X	X	X

Some conclusions can be drawn from Table 1 about the current state of literature in the alternative fuel refueling location problem. Most research has been done on light-duty transport modalities. Most studies do not specify a certain alternative fuel type in their research. For studies in this area, path-based model choices are most commonly used and both linear and non-linear models are used. Most studies focus on a single class in their model. Nearly all studies only focus on Pipeline-To-Modality. The concept of Truck-To-Modality was introduced by Ursavas, Zhu & Savelsbergh (2020) to include the possibility of having trucks refuel transportation modalities on various locations.

In the literature for refueling location problems for alternative fuel types, a keystone is the Flow Refueling Location Model (FRLM) developed by Kuby and Lim (2005). In the FRLM demand is based on origin-destination flow which is either served or not served by a refueling location. When a location serves more flow it scores higher than locations that serve less flow. Many experts built further on the FRLM from Kuby and Lim. The addition of multi-class vehicles by Hwang et al. (2017), is an addition that makes it possible to include different vehicle types with different fuel patterns. Another extension to the model is the addition of the Pipeline-to-Ship and Truck-To-Ship options which were introduced by Ursavas, Zhu & Savelsbergh (2020). This makes it possible to have different types of refueling in the FRLM. In this study, the FRLM has been applied to the maritime transport sector.

This research will be an extension of the work of Ursavas, Zhu & Savelsbergh (2020). This study will make the extension to make the FRLM suitable for maritime hydrogen-based transport with suiting constraints and parameters. Differences that will be incorporated in this study are the usage of hydrogen, the characteristics of hydrogen, and the inclusion of the possibility to have different refueling locations in terms of filling speed, resulting in higher capacity. The specific implications of these characteristics can be seen in section 3.

2.3. Barriers

To make the transition to a maritime hydrogen-based transport sector there are significant barriers to overcome. These barriers can be technological, economic, and political of nature.

2.3.1. Technological barriers

The first type of barrier is the technological barrier. Three important technological barriers have been identified. The first identified technological barrier that the maritime sector has to overcome is that the current state of maritime hydrogen technologies is not as advanced as it is for land-based hydrogen technologies (Van Hoecke, et al., 2020). The most important reason for this is that ships are heavy and require a high amount of power. At this moment most hydrogen techniques are developed for light-duty vehicles and cannot efficiently deliver that amount of power yet (Forrest, et al., 2020). The technologies to have inland cargo ships run on hydrogen are available but not refined and at high costs. For cargo ships that are already in use, it is possible to retrofit the ships to work on hydrogen, but this comes with a large overhaul and high costs (Keizer, et al., 2019). Retrofitting cargo ships makes the ships less fuel-efficient than new hydrogen-fueled ships would be. However, retrofitting will be essential to increase the market share of hydrogen-fueled cargo ships. Retrofitting newer ships is more cost-efficient since the expected lifetime of newer ships is higher and the owners are not expected to purchase a new ship again soon.

A second technological barrier is that it is difficult and costly to transfer large amounts of hydrogen to a large tank at once, like a ship requires (Forrest, et al., 2020; Van Hoecke, et al., 2020). To avoid long refueling times and congestion at refueling locations, a fast and high capacity refueling machine is necessary, which are expensive to manufacture or purchase.

The refueling infrastructure is a third technological barrier, being a prerequisite for a hydrogen-based transport system (Yanfei & Kimura, 2021). To solve this problem, a start has to be made in the refueling location infrastructure to make the adoption of hydrogen-fueled maritime transport more attractive. When the infrastructure will start with a single or a few refueling locations, owners of hydrogen-fueled cargo ships may have to deviate from their original routes. Deviating far from original travel routes can be a barrier for potential customers to switch to alternative fuel modalities (Arslan, et al., 2019). The expectation in the research of Yanfei & Kimura (2021) is that for hydrogen-based transport the number of refueling locations will grow exponentially.

2.3.2. Economic barriers

The second type of barrier is the economic barrier. Three main economic barriers are the lack of funding for large investments, the price and scarcity of green hydrogen, and the competition in the fuel market. Currently, most hydrogen projects are financed by subsidies from governmental authorities. For hydrogen refueling stations this is necessary at this point in time to compensate for both high initial capital costs and high recurring operation and maintenance costs (Kang & Recker, 2015; Xu, et al., 2020). Opposed to that, banks are reluctant to finance hydrogen-themed projects due to existing insecurities on the future of hydrogen. Another reason hydrogen usage in the transport sector is negligible at this point in time is the high prices for the few options in hydrogen-based transport (Ajanovic & Haas, 2018). At this moment fuel cell vehicles are significantly more expensive in current capital costs, fuel costs, and infrastructure costs compared to fossil fuel vehicles and electric vehicles (Staffell, et al., 2019). However, due to technological innovations, these prices are expected to drop so much, that Ajanovic & Haas (2018) expect hydrogen to be the dominant fuel type in the whole transport sector in 2040.

An additional economic barrier for hydrogen is that hydrogen can come as grey, blue or green hydrogen, which have different prices (Velazquez Abad & Dodds, 2020). Grey hydrogen is made by reforming natural gas. Hydrogen can be called blue hydrogen when 80-90% of the carbon dioxide is captured in the production process. Hydrogen is named green hydrogen when it is extracted from renewable energy sources, such as wind or solar energy (Marino, et al., 2019; Qolipour, et al., 2017). Green hydrogen is scarce and substantially more expensive compared to grey and blue hydrogen (Al-Sharafi, et al., 2017; Kothari, et al., 2008). An important reason for this is that it is expensive to mass-produce green hydrogen (Rabiee, et al., 2021). Due to the higher production costs, the costs for customers are higher. However, in some industries, potential customers are willing to pay more for a more sustainable fuel source (Hickson, et al., 2007). No research has been done yet on the willingness of inland cargo vessel owners to pay a higher price for green hydrogen.

A third economic barrier is competition in the fuel market. Three main competitors to hydrogen are identified from the literature. The first one, conventional fossilized fuels, is currently mainly used in the inland shipping sector. Their costs are low and production and distribution processes are optimized, but they pollute too much to be used endlessly. A second competitor, LNG, is less polluting and an alternative for heavy-duty modalities, is already in use (Langshaw, et al., 2020). Using LNG does, however, only cut between 20 and 28% of carbon emissions (Balcombe, et al., 2021; Peng, et al., 2021). Ammonia can be seen as a third competitor. Even though ammonia is a hydrogen carrier, the production process and logistics are completely different (Perčić, et al., 2021). Having a higher energy density, ammonia can be interesting for long-distance shipping.

2.3.3. Political/Legal barriers

The third type of barrier is political/legal barriers. Two main political/legal barriers that are identified are the public view on hydrogen and hydrogen regulation. The way governments deal with the use of fossil fuel types in the future may decide how the public view on the transition to renewable fuel types changes. To gain the acceptance of the public, governments have to adopt suiting policies (Huijts, et al., 2013). One of the most important findings from Huijts et al. (2013) is that both moral considerations from the public and self-interest should be supported by policy. Moral considerations lead to people behaving in favor of hydrogen technologies if they feel like it will help reach environmental goals. Self-interest makes people believe they get value from developments.

When looking at hydrogen as a fuel for inland cargo shipping, international regulation needs to be taken into account (Floristean & Brahy, 2019). The European Union stated regulations and directives affecting the deployment of hydrogen technologies in HyLAW. When looking at hydrogen refueling locations some regulations have to be obliged on safety requirements and maximum storage size. For hydrogen in maritime transport more specific regulations on safety, bunkering, and refueling are given. Besides the HyLAW, there is more regulation for hydrogen storage and transport. HySafe is an international research project where hydrogen technologies were explored and potential hazards were identified (HySafe, 2006). Based on these hazards, safety regulations and measures are stated. The most important hazard identified is the potential of an explosion. For this potential hazard safety barriers and measures for the storage of hydrogen are stated in HySafe.

Hydrogen is considered a dangerous substance by the European Chemicals Agency for two reasons, it is extremely flammable and can be stored as a highly pressurized gas. For the transport of dangerous substances by inland waterways in Europe ADN-regulation is made (United Nations, 2019). In the ADN-regulation requirements for a wide variety of subjects are found. These subjects include requirements on the construction of ships that carry dangerous goods, regulation for the vessel crew, equipment requirements, and loading requirements. While this regulation is aimed at the carriage of the goods and not for the fuel of the vessels, the regulation still needs to be followed until specific regulation for hydrogen is created. Most regulation is aimed at small scale hydrogen usage, while for maritime applications large scale is necessary. The International Maritime Organization develops uniform and internationally available safety and environment standards. An example of a standard like this is an emission limit on sulfur that is introduced in 2020 (International Maritime Organization, 2020). Xu et al. (2020) found that at this point the regulatory approval and permit procedure for hydrogen projects is too complex and not fast enough. New systems involving hydrogen technologies need to be implemented or older systems have to be adapted to be more welcoming to new technologies in this area.

3. METHODOLOGY

In this section, the methodology of this research will be explained. This study consists of qualitative and quantitative research. The quantitative part will consist of a model that will be made to look at the placement of hydrogen refueling locations. To find fitting parameters for the model and roadmap, several interviews are held with experts in this area. This chapter will be structured as follows. First, the problem will be described and, afterwards, the mathematical model will be explained in detail.

3.1. Problem description

Currently, there is no hydrogen infrastructure for ships. It is expected that in the coming decades the usage of hydrogen in ships will grow significantly. To facilitate these ships a refueling location network needs to be rolled out. However, it is not desirable to place a great number of refueling locations, due to high investment costs and relatively low demand. In Figure 2 the problem this research will focus on is visualized. First, hydrogen has to be produced by electrolyzing energy from varying sources. This hydrogen thereafter will be used in either a Truck-To-Ship (TTS) or Pipeline-To-Ship (PTS) refueling location. The hydrogen is being used as fuel in fuel cells of inland cargo ships. In this research, distinction is made between normal and fast refueling speed of refueling locations. Faster refueling speed makes the refueling location have higher capacity, at the cost of more initial and operational costs.

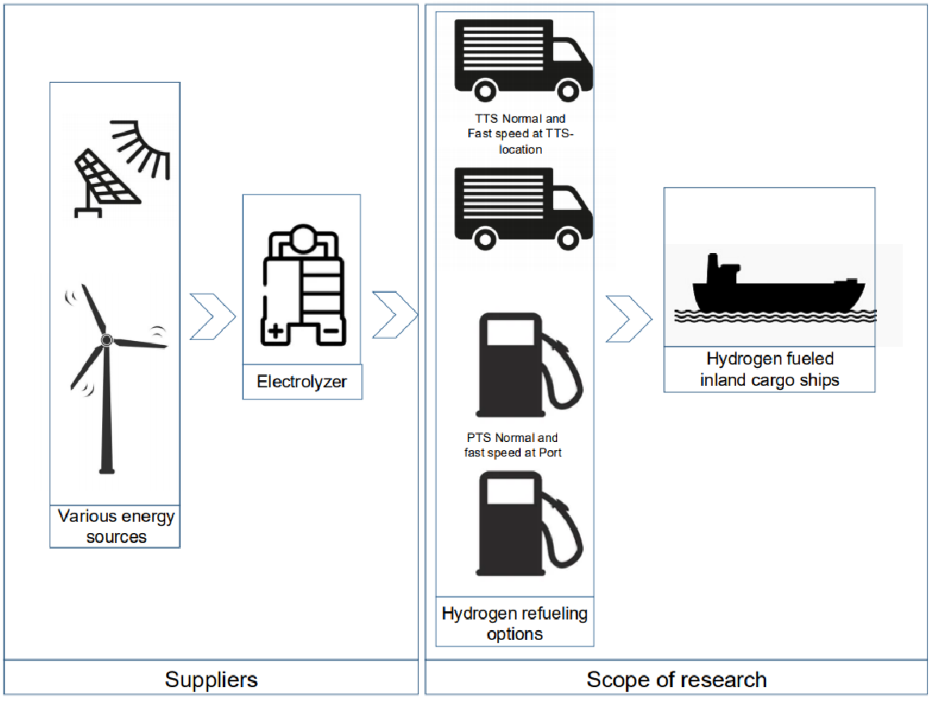

Figure 2: Problem description

For this research, a path-based refueling location model is the most fitting, due to inland cargo ships having clear paths with fixed traveling routes with clear origins and destinations. Node-based refueling location models do not fit because for maritime refueling locations, the locations are generally bound to large waterways, where node-based refueling location models place refueling locations in centroids of demand areas.

The FRLM from Kuby & Lim (2005) is the path-based refueling location model that is chosen. This model was proven in various settings and known to deliver trustworthy output. This model from Kuby & Lim was extended by Ursavas, Zhu & Savelsbergh (2020) to fit with multi-class ships fueled with LNG. In this extension, the possibility of fueling truck-to-ship was included. For this research, this extension from Ursavas, Zhu & Savelsbergh (2020) was taken as starting point. In this research this model will be firstly adapted to fit the characteristics of hydrogen, removing or adapting the LNG-specific parameters and decision variables. It will be extended with the possibility to decide if a refueling location fills at normal speed or fast speed. This influences the costs, capacities, and revenues of the refueling infrastructure.

3.2. Mathematical model

In this model, a waterway network with nodes from set N in arc set A is used. Within this network set of origin-destination pairs Q is used to define the demand in the area. A refueling location is assumed to be an origin or destination of a trip. Each O-D pair has an origin, destination, distance in km $d(i,j)$, and flow f_q. The assumption is made that not all flow has to be covered. Another assumption is that whenever a refueling location is present at both origin and destination, the flow is equally divided between both refueling locations. In set L all possible locations for a refueling location are given, with a division in what types are available at what location. The binary value y_{ic} decides whether a facility type c is operated at location i. The different facility types are named in set C, with their respective characteristics as capacities c_i, initial costs u (i,c), and operating costs $o(i,c)$. The costs are capped on a maximum budget I.

Four different types of refueling stations are considered in this model, PTS, TTS, Fast PTS, and Fast TTS. TTS locations can deliver hydrogen at multiple predefined locations, while PTS locations are stationary at one location. Fast locations have increased daily capacity. For the TTS refueling stations, additional costs k are modeled in to move hydrogen amount w from location i to j.

Within this waterway network, ships from the set of ship types S are included in the model. The revenue of the refueling location is modeled as hydrogen consumption l of ship S between location i and j, which can be multiplied by the selling price for hydrogen h. An assumption is made that ships always refuel to a full tank.

The model used in this report uses the sets, parameters, and decision variables described in respectively Table 2, Table 3, and Table 4.

Table 2: Sets

Set	*Description*
$\boldsymbol{Q}$	Set of origin-destination (O-D) pairs
$\boldsymbol{Nq}$	Set of nodes associated with shipping route q
$\boldsymbol{Aq}$	Set of arcs associated with shipping route q
$\boldsymbol{L}$	Set of nodes where it is possible to operate a refueling location (PTS and TTS)
$\boldsymbol{C}$	Set of facility types (with capacities, normal/fast speed, TTS)
$\boldsymbol{S}$	Set of ship types (with fuel usage, range, tank size)

Table 3: Parameters

Parameter	*Description*
$\boldsymbol{f_q}$	Demand on the shipping route *q*
$\boldsymbol{d(i,j)}$	Distance between locations *i* and *j* (in km)
$\boldsymbol{l(i,j)}$	Hydrogen consumption of ship of type s on a trip from node i to *j*
$\boldsymbol{h}$	Selling price of hydrogen (per kg)
$\boldsymbol{t_c}$	Capacity of a facility type *c*
$\boldsymbol{I}$	Budget
$\boldsymbol{o(i,c)}$	Operational costs of operating a facility of type *c* on location *i*
$\boldsymbol{k(i,j)}$	Costs of transporting hydrogen from location *i* to location *j*

Table 4: Decision Variables

Variable	*Description*
$\boldsymbol{y_{ic}}$	Binary value: 1 if a refueling location of type c is operated at location i, 0 if not
$\boldsymbol{v_{ij}^q}$	The fraction of the demand of shipping route q that uses arc *(i,j)*
$\boldsymbol{w_{ij}}$	Amount of hydrogen (in kg) transported from a TTS location *i* to location *j*

The model:

$$Z = hl \sum_{q\in Q} \sum_{i\in N^q} \sum_{j\in N^q} d(i,j)\, v_{ij}^q f_q - \sum_{i\in L} \sum_{c\in C} o(i,c)\, y_{ic} - \sum_{i\in L} \sum_{j\in N} k(i,j)\, w_{ij} \quad (1)$$

Subject to:

$$\sum_{i\in L} \sum_{c\in C} o(i,c)\, y_{ic} + \sum_{i\in L} \sum_{j\in N} k(i,j)\, w_{ij} \le I \quad (2)$$

$$0 \le v_{ij}^q \le 1 \quad (3)$$

$$0 \le w_{ij} \le t_c \quad (4)$$

$$y_{ic} \in \{0,1\} \qquad \forall i \in L, c \in C \quad (5)$$

The objective of the model is to maximize profit. The model has three terms. In the first term of the model, the revenue from hydrogen usage by ships is given. In the second term, the costs of operating and resupplying are calculated. The third term takes the additional costs relating to TTS locations into account. The model is subject to four constraints. The first constraint ensures that the budget for the project is not exceeded. The second constraint ensures that the demand using arc i,j is given as a percentage. The third constraint ensures that the amount of hydrogen transported from a TTS location is never more than the capacity of the refueling location. The fourth constraint ensures that decision variable y_{ic} is binary.

3.2. Case study methodology

A case study will be done to combine the qualitative and quantitative data acquired into a real-life situation. Semi-structured interviews are being held with stakeholders in the area of interest. Parameters for the model are based on interviews, reports, and observations. In the case study, sensitivity analyses are held to identify the effects of changes in parameters.

4. CASE STUDY

In this section, the case study will be discussed. First, the case selection will be elaborated and afterwards the data collection process will be explained. Lastly, the different scenarios will be shortly explained.

4.1. Case selection

The scope of this case study is the area visualized in Figure 3. This area includes parts of the Netherlands and Germany. Within this area interviews have been held with a fuel company, a port company, a shipbuilder company, and an inland cargo shipping company. Table 5 shows all possible refueling locations in this area of interest, which have been chosen based on the number of cargo vessels traveling from and to the port.

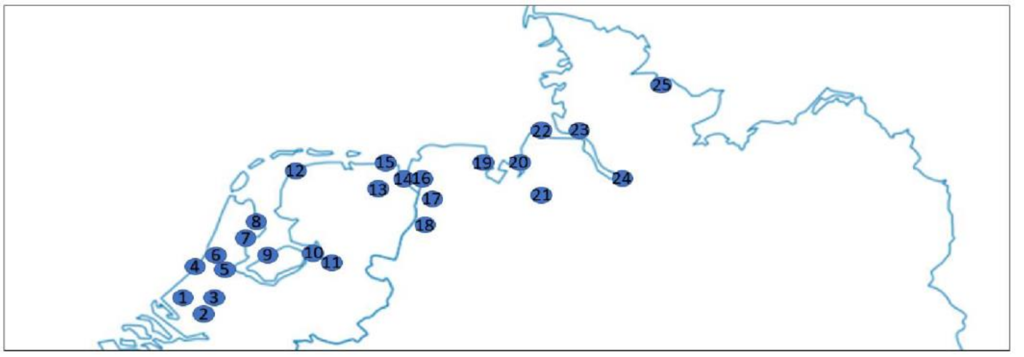

Figure 3: Locations of ports in area of interest

Table 5: Possible hydrogen refueling locations in ports

Port number	*Possible PTS location*	*Port number*	*Possible PTS location*
1	Rotterdam	14	Delfzijl
2	Dordrecht	15	Eemshaven
3	Gouda	16	Emden
4	Ijmuiden	17	Leer
5	Amsterdam	18	Haren
6	Zaandam	19	Wilhelmshaven
7	Hoorn	20	Bremerhaven
8	Enkhuizen	21	Bremen
9	Lelystad	22	Cuxhaven
10	Kampen	23	Brunsbüttel
11	Zwolle	24	Hamburg
12	Harlingen	25	Kiel
13	Groningen		

From these 25 locations, four possible TTS locations have been identified. It is possible to run a TTS location when multiple possible port locations are geographically proximate and are easily accessible with trucks from a central point. The assumption is made that within these areas it is possible to set up a TTS service with sufficient hydrogen supply. The four locations for TTS service are visualized in Figure 4 and further specified in Table 6.

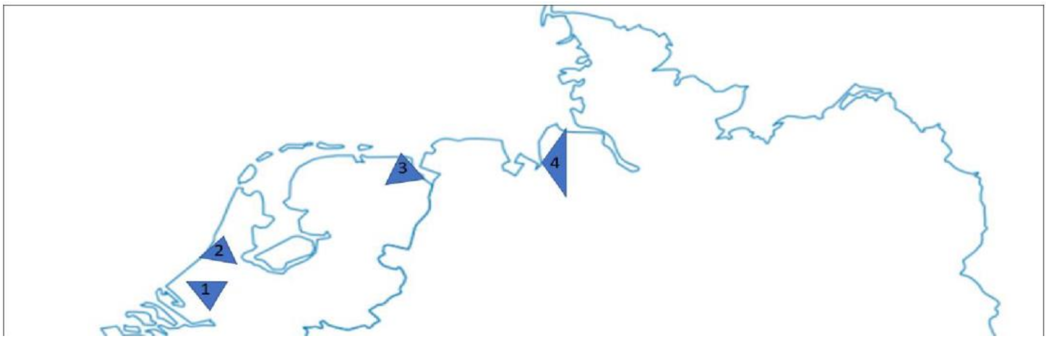

Figure 4: Locations of possible TTS locations

Table 6: Possible TTS locations

Possible TTS Location	*Ports serviced in area*
1	Rotterdam, Dordrecht, and Gouda
2	IJmuiden, Amsterdam, and Zaandam
3	Groningen, Delfzijl, and Eemshaven
4	Bremerhaven, Bremen, and Cuxhaven

4.2. Data collection

In 2019, 5040 vessels were registered in the Netherlands as barge (CBS, 2019). However, this is not a representation of the entire population of cargo ships active in the area of interest, since only a fraction of these ships travels within the area of interest. Another factor to take into account is that ships from other countries are active in the area of interest. Therefore, another way of determining the population is necessary. As an alternative, for this study data has been obtained from the FleetMon database, which holds historical data with port calls, dates, and ship details for all large ships (Fleetmon, 2021). 200 inland cargo ships have been identified that operate in the area of interest. From these 200 ships data on 4998 combined trips with an origin and destination within the area of interest has been collected. The distance between ports over waterways has been calculated with the Navionics app, which is a nautical GPS plotter (Navionics, 2021).

4.2.1. Bias correction

These 5000 trips give a good overview of the patterns within this area. However, there are some biases due to problems with this data. The first bias is that the data is from the 1st of December 2020 until the 1st of May 2021, due to the data in the database only being accessible to the author for six months, with a planned backup period of one month. There might be a seasonality bias involved in the data where certain seasons are more popular due to better weather conditions. The second problem is uncertainty on how large the proportion of the total population the sample is.

To solve these two problems data from two ports within the area of interest has been received from the port company. This data includes all port calls of the year 2020 for those ports. At these ports, a total of 3737 cargo ships have arrived in 2020. The division of arrivals per month is visualized in Figure 5. From the figure can be concluded that a seasonality effect in the number of ships arriving exists. In the summer period, more ships arrive. The assumption is made that the seasonality of these two ports is representative for all ports in the area of interest. From the 3737 ships, 1480 ships arrived in the months December, January, February, March, and April. This is a fraction of 39,61%, so to gain demand for a full year the demand has to be multiplied with a factor of 2,525. This factor will be included when calculating the total demand for a year for every origin-destination pair after solving the next problem.

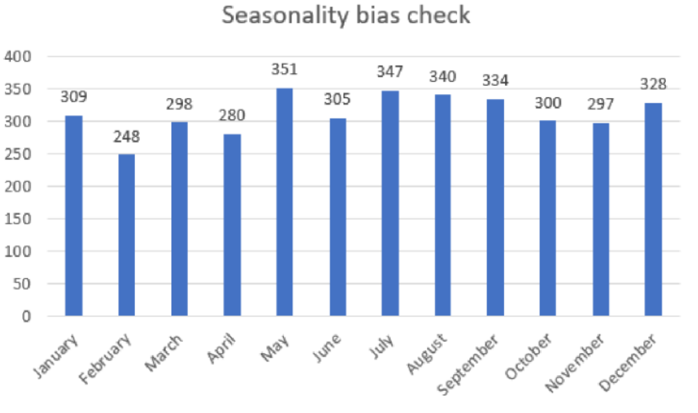

Figure 5: Seasonality bias check

For the second problem, the proportion of the sample size of the full population of cargo ships, the same data from the port company is used. To make an accurate comparison, the months of January, February, March, April, and December have been taken from the data. The data collected from FleetMon consists of 406 port calls for the ports, while the realized data for the same period consists of 1480 port calls. This indicates that a sample size of 27,43% has been taken from the full population. To find the demand of the full population over a full year, the data first has to be multiplied with a factor of 3,465 to have the demand of the full population and afterwards with a factor of 2,525 to have the demand for a full year.

4.2.2. Ship type classification

The ships in the area of interest are categorized by length. The ships are classified into four categories which are shown in Table 7. Categorizing by length makes it possible to have more accurate demand

and usage patterns of hydrogen in the area. The categories are in line with the CEMT-classification of Rijkswaterstaat (Rijkswaterstaat, 2011). In this categorization, the ships are categorized on comparable tonnage, length, and width. The decision was made to include one more categorization point at 95 meters. The reasoning for this is that the M6 class in the CEMT-classification is very broad, ranging from 80 to 105 meters. Within this class, large differences are present. The hydrogen usage and retrofitting costs estimations in the model are based on the different classes of the ships. The usage of the ships, hydrogen usage, and retrofitting costs are based on interviews and calculated estimates.

Table 7: Ship class specifications

Ship class	*Ship length (m)*	*CEMT-classification*	*Hydrogen usage (kg/km)*	*Retrofitting costs (euros)*
1	60-79	M3, M4	1.4	1.750.000
2	80-94	M5, M6 < 95	1.55	2.150.000
3	95-109	M6 ≥ 95, M7	1.75	2.550.000
4	110+	M8	2.00	3.000.000

4.2.3. Refueling location classification

In this case study, four different types of refueling locations are distinguished. The characteristics of these four types are presented in Table 8. The information to determine initial prices, operational costs and capacity comes from Company A and a report on hydrogen station compression, storage, dispensing, technical status, and costs from the U.S. Department of Energy Hydrogen and Fuel Cell Program (2014).

Table 8: Characteristics of the different type of refueling locations

Type of station	*Initial price in euros*	*Operational costs (differs per scenario)*	*Capacity*	*Method*
Low speed	1569000	X% of Initial price + hydrogen costs	730000	2000 kilo hydrogen per day
High speed	2324625	X% of Initial price + hydrogen costs	1095000	3000 kilo hydrogen per day
TTS Low speed	1812400	X% of Initial price + hydrogen costs + transport costs	730000	2 trucks with 500 kilo hydrogen that can do 2 trips a day
TTS High speed	2616625	X% of Initial price + hydrogen costs + transport costs	1095000	2 trucks with 500 kilo hydrogen that can do 3 trips a day

4.3. Scenarios

For this case study, different scenarios have been set for the years of 2030, 2040, and 2050 to combine them into a roadmap to 2050. In Table 9, the different settings for the scenarios are presented. Parameters for the model for costs, market growth, and selling prices are presented here. The scenarios are based on interviews, information from Company A, and multiple reports. For the growth in shipping volume, a report on growth in the inland shipping industry from Panteia (2017) is used. In this report, it is calculated that the average growth in the Dutch inland cargo industry is growing by 1.57% every year. The assumption is made that this growth will continue. The other scenario parameters of prices, availability, and capacity of refueling locations is obtained at Company A and from a report on hydrogen station compression, storage, dispensing, technical status, and costs from the U.S. Department of Energy Hydrogen and Fuel Cell Program (2014).

Table 9: Characteristics of the different scenario's

	2030	**2040**	**2050**
Growth in shipping volume	101.57%^9	101.57%^19	101.57%^29
Price purchase of hydrogen	2,50	2,00	1,00

Price hydrogen sale slow	4,00	3,00	2,00
Price hydrogen sale fast	4,50	3,50	2,50
Percentage of the current prices for refueling stations	75%	50%	30%
Percentage vessels on hydrogen	1%	10%	50%
Capacity refueling stations	70%	98%	120%
Maintenance costs	6% of initial costs	4% of initial costs	4% of initial costs

The way hydrogen will be fueled in all scenarios is in pressurized gas form compressed at 300 bar. Both literature and interviews indicate that this is the most realistic option at this point in time, since hydrogen needs more storage room compared to fossil fuels, and this room will be saved with hydrogen on higher pressure. Pressurizing hydrogen further is too expensive in the scale needed for inland cargo ships. In the future the way hydrogen is used as fuel may differ.

5. RESULTS

In this section, the results of the research, gathered with the use of Microsoft Excel and the Excel Solver, will be presented. First, considerations about the different locations regardless of the scenario are made. Afterwards, the results for the different timestamps in the roadmap, being 2030, 2040, and 2050, are given and explained. These results are combined in a clear visualization of the roadmap. Lastly, the key findings from the interviews will be given.

5.1. Flow in the area of interest and general remarks

In the area of interest, the demand is calculated by the number of ships that travel an O-D path. 161 different O-D paths that are actively used are identified. In Table 10, the total demand for the ten O-D paths with the highest demand is presented. In the first two columns, the origin and destination of a trip are given. In the five columns afterwards, the total amount of ships traveling the route and the division between the ship classes is given. Combining the different usage patterns of the ship classes, the distance between origin and destination, the number of ships using the route, the growth factor from the scenario (see Sect. 4.3), and the bias correction (see Sect. 4.2.1.), gives the total demand for a route. The demand visualized is from scenario 2030.

Table 10: Ten Origin-Destination pairs with the highest demand

Origin	Destination	Total	Flow Ship Class 1	Flow Ship Class 2	Flow Ship Class 3	Flow Ship Class 4	Distance (kms)	Total demand in kg
1	**5**	740	46	285	23	386	82	14344
5	**14**	168	13	95	12	48	223	10522
23	**24**	327	21	128	178	0	82	9294
5	**9**	580	79	326	33	142	52	8650
9	**14**	131	5	76	10	40	173	6304
23	**25**	163	26	98	33	6	106	5679
1	**9**	118	2	54	6	56	121	3521
20	**21**	135	1	130	4	0	71	3203
1	**14**	45	1	21	1	22	292	3194
16	**18**	74	0	73	1	0	115	2842

The patterns of the total demand are assumed to remain similar in all scenarios. That makes it possible to tell which possible refueling location covers the largest amount of flow when a single hydrogen refueling location would be placed on that location, regardless of the scenario. Figure 6 shows all possible refueling locations and the percentage of flow that would be captured if that location was the only active location.

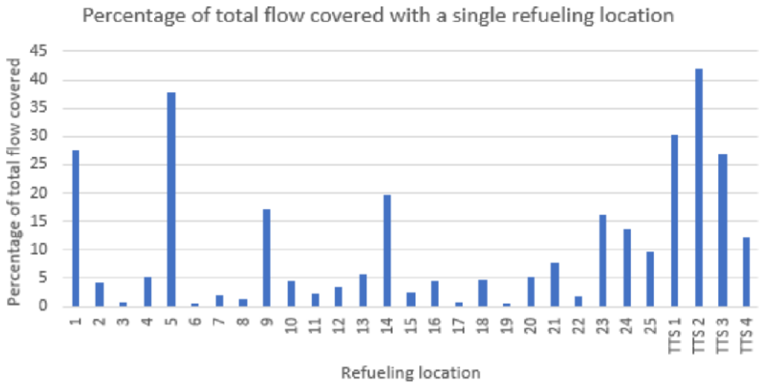

Figure 6: Percentage of total flow covered with a single refueling location

5.2. Roadmap to 2050

In this section, the results for the different timestamps in the roadmap to 2050, being 2030, 2040, and 2050 will be given. For every timestamp, the optimal solution, additional analyses, and a conclusion are given.

5.2.1. 2030

In the year 2030, the foundation of a hydrogen refueling network needs to be placed. In 2030, the expected percentage of ships fueled by hydrogen is 1%. It is not expected that a large number of vessel owners are considering switching to hydrogen this early.

The optimal solution to maximize the profit that appears as output of the model is visualized in Figure 7. One normal speed refueling location is placed in Amsterdam, with a minor profit. When including a second normal speed refueling location in Rotterdam there is a yearly money loss. In Table 11, the optimal situation is compared to the next best situation. What can be seen is that even though the optimal situation has a small yearly profit, this is not high enough to make up for the high initial costs. The availability of a solution gives the percentage of total flow that is covered by the active refueling locations. The efficiency of a solution shows the percentage of the total capacity of the refueling locations that is being used to cover the demand. The economic performance is explained by demand being low, which makes it hard to operate multiple hydrogen refueling stations of any type with profit.

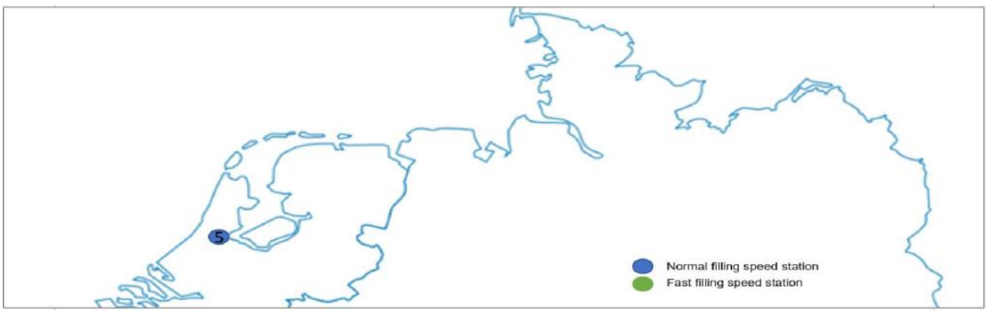

Figure 7: The optimal solution in 2030

Table 11: Comparison optimal solution

Locations	*Availability*	*Efficiency*	*Initial Costs*	*Operational costs per year*	*Yearly revenues*	*Yearly profit*
1	37,71399	0,105284	1176750	205105,5	215200,8	10095,32
1, 5	55,31815	0,077214	2353500	338492,8	315652,4	-22840,3

From interviews and literature, it becomes clear that the availability of refueling locations is essential for the success of the implementation of a refueling network. For that reason, the optimal solution of placing one refueling location in Amsterdam might be the most cost-efficient, but it helps minimally towards the success of the entire network. Governmental aid is essential to set up more than one refueling location. To give the refueling network a head start, a solution is to maximize availability.

When the network is ready, it can incentivize vessel owners to switch to ships on hydrogen. Figure 8 presents a sensitivity analysis that reveals the effect of including a set amount of refueling locations on the coverage of the network. The refueling stations have been selected on having the biggest effect on the coverage. As seen, the increase in coverage becomes smaller for every additional refueling location placed.

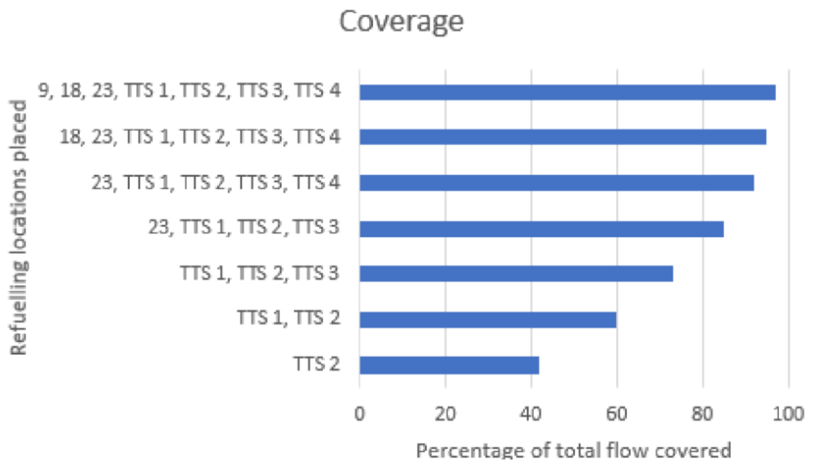

Figure 8: Sensitivity analysis with a set amount of refueling locations

To efficiently start the hydrogen refueling network, high coverage is wanted in the early years. If a goal would be set to reach 90% coverage, five stations have to be placed at the four TTS locations and one in Brunsbüttel. This solution is visualized in Figure 9.

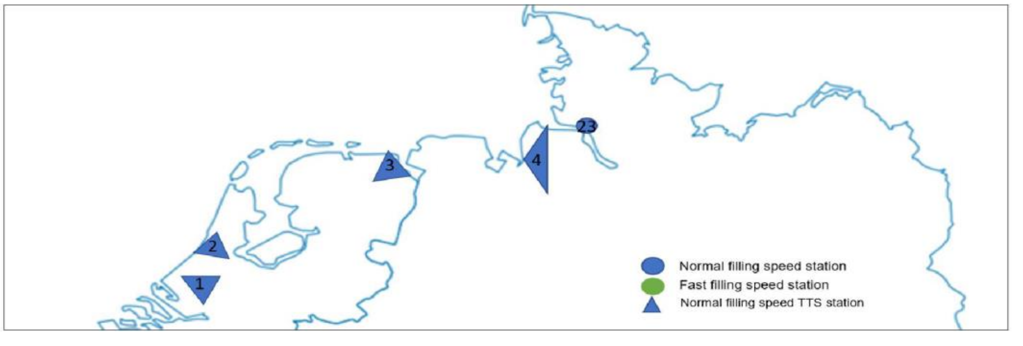

Figure 9: Suggested solution in 2030

Interesting to see in Figure 8, is that TTS locations are often chosen when maximizing coverage. This is explained by the nature of TTS locations, which cover larger areas with a single refueling station. In Figure 10, the costs and benefits for these situations are visualized. As seen a significant investment from governments would be required both for the initial costs and for the negative yearly profit.

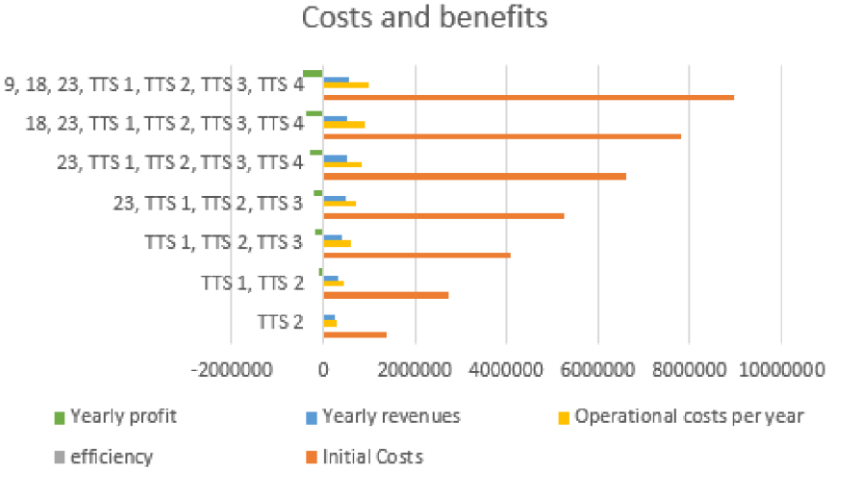

Figure 10: Costs and benefits for a different amount of refueling locations placed

Conclusion 2030 Running a hydrogen refueling network for inland cargo ships will not be economically feasible in 2030 without governmental aid. To maximize the effects of governmental aid the investments should be done in maximizing the coverage of the hydrogen refueling network. A suggested refueling network for 2030 has been presented including five refueling locations, of which four are TTS. In this situation, 92,15% of the flow is covered, but there are initial starting costs of €6.613.950,- and yearly losses of €310.863,- that have to be compensated by governments.

5.2.2. 2040

In the year 2040, the percentage of inland cargo ships fueled with hydrogen is estimated to be 10%. It is expected that a significant part of vessel owners have switched and that it has become cheaper to retrofit/build a ship, produce hydrogen, and run a hydrogen refueling station.

In 2040, the optimal solution is to place a normal speed location at Rotterdam, Amsterdam, Lelystad, Delfzijl, Haren, Bremen, Brunsbüttel, and Hamburg, making a total of 8 refueling stations. The optimal solution is visualized in Figure 11. The fraction of the total flow that is covered by this network is 94,15%. Different from the situation in 2030 is that multiple refueling locations can operate with yearly profit in the area of interest without the need for governmental aid. This can be explained by the demand for hydrogen being sufficient to cover the variable costs. In this scenario, the breakeven demand to cover the variable costs is 25.104 kilograms of hydrogen. The demand is insufficient to justify placing high speed refueling locations instead of normal speed refueling locations. For the first few stations, the payback period is a few years, while for the latter stations this period is longer. In Figure 12, a sensitivity analysis on the maximum amount of refueling locations that are placed is presented. The yearly profit and marginal profit of optimally placing between 1 and 9 refueling locations can be seen. The optimum is recognized as the last station with a positive marginal profit.

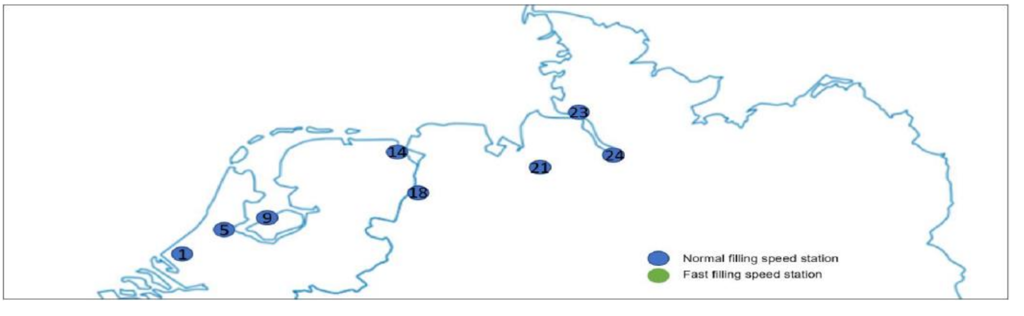

Figure 11: The optimal solution in 2040

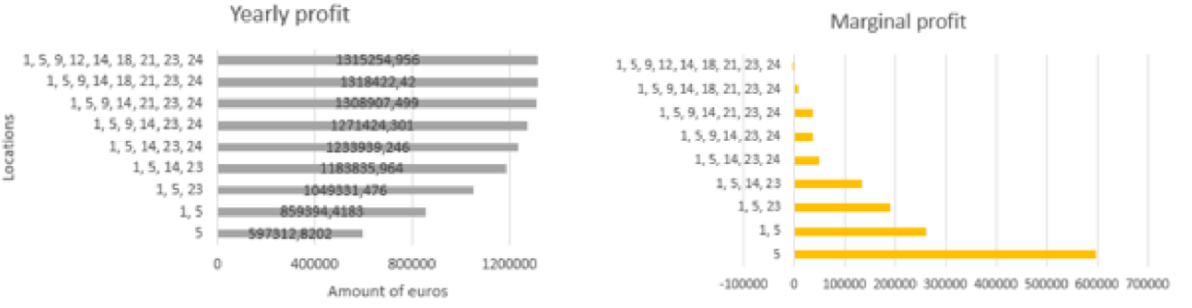

Figure 12: Sensitivity analysis on yearly and marginal profit for a set amount of refueling locations in 2040

Interestingly, no TTS locations have been chosen in the optimal situation. This is explained by the high operational costs that come with TTS locations when the demand for hydrogen becomes higher. For PTS locations, these operational costs are lower. The differences between TTS and PTS locations in ratios are presented in Table 12. In this figure, a situation with 7 coverage maximizing refueling locations (including 4 TTS locations) is compared with the optimized situation, limited to 7 refueling locations. The biggest difference lays in the higher operational costs when TTS locations are involved, resulting in significantly less yearly profit.

Table 12: Comparison between coverage maximization and costs optimization

	Coverage maximizing locations	*Profit optimized locations*	*Difference in percentage*
Locations active	9, 18, 23, TTS 1, TTS 2, TTS 3, TTS 4	1, 5, 9, 14, 21, 23, 24	
Coverage	96,97%	91,70%	-5,43%
Initial costs in euros	€ 5.978.300,-	€ 5.491.500,-	-8,14%
Yearly operational costs in euros	€ 4.226.460,-	€ 3.276.795,-	-22,47%
Yearly revenues	€ 4.849.694,-	€ 4.585.702,-	-5,44%
Yearly profit	€ 623.234.-	€ 1.308.907.-	+110,02%

Important to state is that the difference between the purchase and selling price of hydrogen is essential to determine how much room for profit is present. To look at the effects, a sensitivity analysis is done on the difference between buying and selling price. In Table 13, different scenarios on hydrogen prices are given. One scenario is optimistic, one is neutral and one is pessimistic.

Table 13: Different scenarios on hydrogen price

Scenario	*Purchase price*	*Selling price*	*Difference*
Pessimistic	€2,00	€2,75	€0,75
Neutral	€1,75	€3,00	€1,25
Optimistic	€1,50	€3,25	€1,75

For the three different scenarios, three optimized situations are given in Table 14. The amount of locations able to run with profit is higher, the bigger the difference is between purchase and selling price. The yearly profit increases significantly as well when the difference in selling and purchase price increases. The directions of these relations are the same in 2030, 2040, and 2050, although the effect is stronger when the demand increases, due to economies of scale.

Table 14: Optimization results sensitivity analysis on hydrogen price

Scenario	*Amount of Locations*	*Availability*	*Efficiency*	*Initial Costs*	*Yearly operational costs*	*Yearly revenues*	*Yearly profit*
Pessimistic	7	91,69563	0,33237	5491500	3276795	4203561	926765,6
Neutral	8	94,14883	0,298604	6276000	3389965	4708387	1318422
Optimistic	10	97,44051	0,247235	7845000	2750302	5279088	2528786

Conclusion 2040 In 2040 it is economically feasible to run eight normal speed refueling locations with coverage of 94,15% without governmental aid. A yearly profit of €1.318.422,- can be made and the initial starting costs of €6.276.000,- can be earned back in 4,76 years. This buyback period does not include already existing refueling locations/assets. The switch from TTS to PTS is essential to provide more profit.

5.2.3. 2050

In 2050 between 50% and 70% of the emitted greenhouse gasses in maritime transport should be reduced compared to 2008 (International Maritime Organization, 2018). The Dutch national government agrees with this requirement, and also stated that they expect the Dutch inland shipping sector to be climate neutral. Hydrogen is expected to be a large part of the solution to this problem. While there still will be ships fueled on LNG or other fuel types, 50% of the total inland shipping is expected to be fueled with hydrogen. This requires an extensive hydrogen refueling network since the demand will be high.

In 2050 five fast refueling stations will be placed. Two of them in Amsterdam, one in Rotterdam, one in Delfzijl, and one in Brunsbüttel. A normal speed refueling station will be placed in Rotterdam, Lelystad, Bremen, and Hamburg. The optimal solution is visualized in Figure 13. The fraction of the total flow that is covered by these refueling locations is 89,97 percent. This coverage is lower than in 2040, due to Amsterdam not being able to cover all demand with two high speed refueling stations, while placing an additional refueling location would result in a reduction in profit. The breakeven demand for a normal refueling location to be placed is 447.414 kilograms of hydrogen. For a high speed refueling location, this is 670.947,75 kilograms of hydrogen. In Figure 14, a sensitivity analysis is done on the yearly and marginal profit for every optimized situation with a set amount of refueling locations. It can be concluded that nine refueling locations are optimal. Interesting to see is that the marginal profit for the first five refueling locations is the same. This can be explained by these five refueling locations having too much demand, and therefore operating at 100 percent capacity when placed.

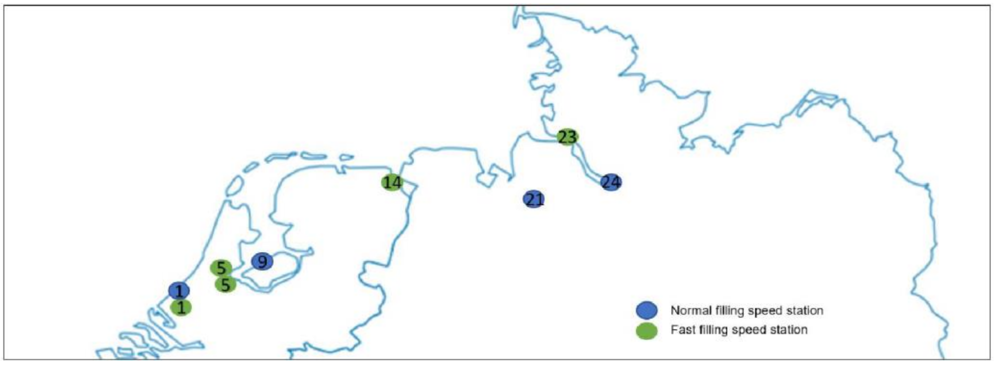

Figure 13: The optimal solution in 2050

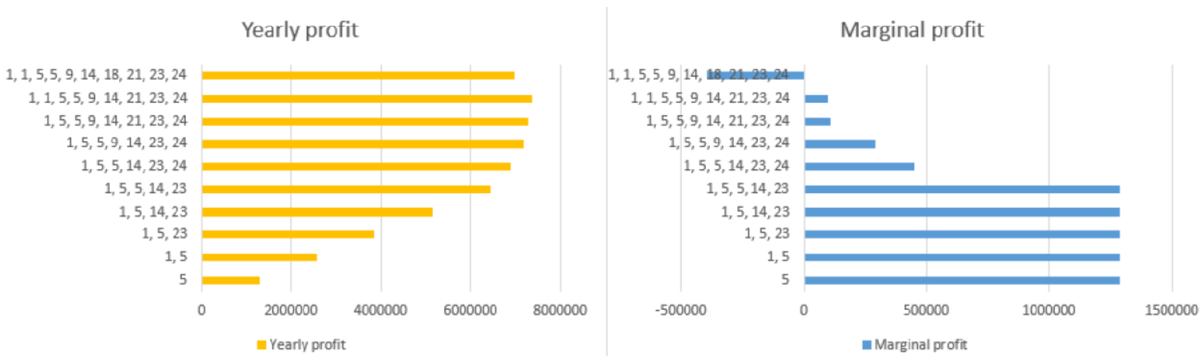

Figure 14: Sensitivity analysis on yearly and marginal profit for a set amount of refueling locations in 2050

The buyback period for the initial costs can be covered within a year. This is explained by lower setup and operational costs, accompanied by a larger demand. In Figure 15, the economic performance is visualized. As seen, the yearly profit is higher than the initial costs of the complete network. When considering that the initial costs will be lower due to an already existing hydrogen network from earlier years, it stands out that this network is economically feasible.

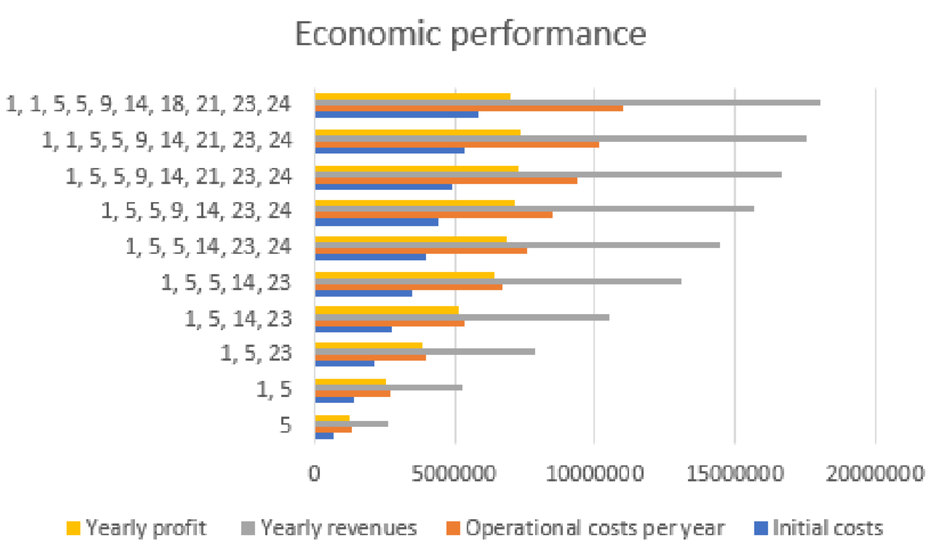

Figure 15: Economic performance of different solutions

Conclusion 2050 In 2050 there is a serious and complete refueling network viable for hydrogen in the inland shipping sector in the area of interest. Five high refueling speed locations and four normal speed refueling locations are placed. This optimal solution has 89,97% coverage. No help from governments is necessary at this point, since the yearly profit of €7.382.802,- is significant and covers the initial costs of €5.369.738,- in 0,73 years. Realistically this buyback period is even lower due to an already existing refueling network from 2040.

5.2.4. Roadmap to 2050

In Figure 16, the roadmap to 2050 with the different milestones discussed in this chapter is given, with concluding results for 2030, 2040, and 2050.

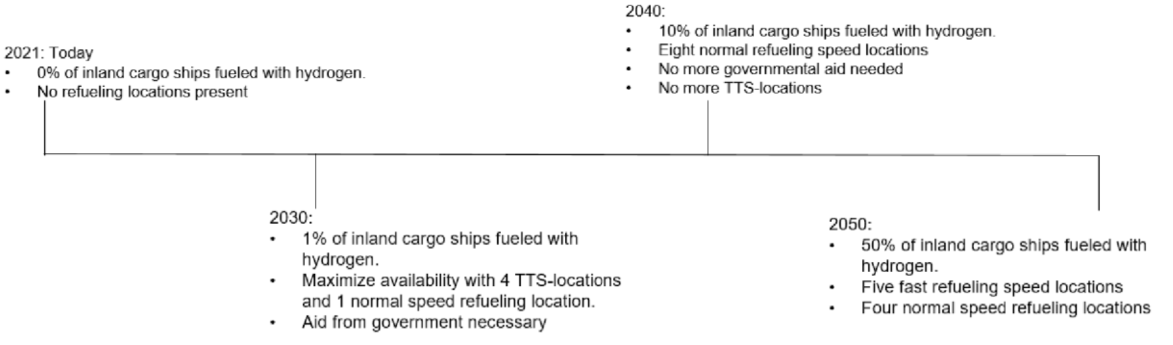

Figure 16: Roadmap to 2050

5.3. Results from interviews

In this section, the key findings from the interviews will be elaborated. The results will be discussed from an economic, technical, and political/legal point of view.

5.3.1. Economic aspects

From an economic point of view, there are serious concerns about the transition to hydrogen. In the short term, costs for providing hydrogen and building or retrofitting a hydrogen ship are very high. The only way this currently is economically feasible is with pioneers that believe in the transition and governments that aid for more than 50%. It is expected that this will be the case for the next years, even though the prices for building and retrofitting are gradually decreasing. There is a substantial amount of subsidies available for making the transition towards a hydrogen-based maritime transport sector. These subsidies are on European, national and regional levels. On the European level, the European Commission launched the European Clean Hydrogen Alliance, which has as one of its goals to support investments in the production and demand of hydrogen. On a national level, the Dutch Government decided in their Climate Agreement (2019) that a National Hydrogen Programme is established that focuses on the hydrogen infrastructure and facilitates current initiatives. On a local level, local governments are eager to cooperate on hydrogen projects and help with financing. There are more specific subsidies available, with as a concrete example the European Green Shipping Guarantee Programme where the purchase of new hydrogen vessels or the retrofitting of older vessels can be partially financed (European Investment bank, 2018).

The aim in the inland cargo shipping world is to make as much profit as possible. In regards to fuel choice, this would mean that switching fuels has to lead to a decrease in costs before ship owners would consider switching to hydrogen. Fuel companies are interested in the transition but are reliant on possible profit since the profit margins are slim in the fuel sector. Most vessel owners in the area work for themselves under an association that arranges the division of trips, so no big players are pushing for radical sustainability goals. Important for the transition is what is going to happen to the conventional fuel types. If the conventional fuel types become significantly more expensive due to governmental tariffs or resource scarcity the transition to more sustainable fuel types might be faster.

In the longer term, opinions are different. All interviewees agree that the transition needs to be made, however, the role of hydrogen is not agreed upon. There are doubts on the role hydrogen will play in the transition, but the consensus is that there currently is no better alternative.

5.3.2. Technical aspects

From a technical point of view, the essence of availability is considered extremely important. A quote from an interview with the vessel owner is: "A lot of sustainable initiatives fail by lacking the actual fuel source". For the maritime hydrogen projects planned at this point in time the way the hydrogen is obtained is determined beforehand. In all maritime projects that the interviewees are part of, the hydrogen is delivered at 300 bar to find balance between costs and storage size. The fuel owner has serious doubts about the energy density of hydrogen. Ammonia, which has a higher energy density, could be serious competition for ships that have to travel longer. The retrofitter and the vessel agree that this could potentially be a problem, but are optimistic about innovations. In general, the view is optimistic on the technical perspective on the future for hydrogen-fueled inland cargo ships. It is already possible to build or manufacture a ship to run on hydrogen and it will only get more cost- and fuel-efficient.

5.3.3. Political/Legal aspects

From a political/legal point of view, one thing stands out from the interviews, that a lack of regulation is present. Nationwide port regulation on hydrogen still has to be made. This is a process that is done in cooperation with multiple ports to avoid ambiguity but it will take a while. At this moment it is not allowed to use hydrogen as a fuel for a ship. The vessel owner that is building a large ship on hydrogen states that his ship will be an exemption that is allowed to travel for research purposes. It takes long to make the required regulation and a lot is not yet known.

On a local level permission is needed from the local government for hydrogen projects. Since knowledge on hydrogen is currently missing in local governments, it can take a relatively long time for local governments to validate the safety of the project and to give permission. Because of this, hydrogen projects often are delayed.

6. DISCUSSION AND MANAGERIAL IMPLICATIONS

In this section, the results of this research will be discussed and compared to the literature. Besides the literature, the results also were discussed with 3 consortium partners to identify insights on the results from experts.

6.1. Roadmap to 2050

The research question of this research is "How can the transition towards a hydrogen-fueled inland cargo ship network be organized most efficiently?" The results section of this study gives insights on how the future hydrogen refueling network should look and what is needed to make it succeed. In the literature, there is at the time of writing, no refueling location model designed for hydrogen in the maritime sector. There are refueling location models that work in specific situations, such as for alternative-fuel cars in a standard environment (Kuby & Lim, 2005), alternative fuel multi-class trucks (Hwang, et al., 2017), and LNG-fueled ships with TTS options (Ursavas, et al., 2020). Adapting the model of Ursavas et al. (2020) to suit hydrogen-fueled ships yields a model that fits the problem well. The results from the model gave clear and realistic outcomes for the years 2030, 2040, and 2050. Using the data from FleetMon and the port company gave a good overview after bias correction for the flow in the area of interest.

For the roadmap, it is suggested by the author to follow the results of the model for 2040 and 2050. For 2030, however, another approach is necessary to help the hydrogen network over the so-called 'chicken-and-egg problem' (Kang & Recker, 2015). For the year 2030, the suggestion is to work with a coverage maximizing approach instead of a cost-minimizing approach. Significant investments from the Dutch and German governments will be needed to speed up the transition to hydrogen being a commonly used fuel type for maritime transport. The suggested refueling network in 2030 is to place four TTS locations and 1 normal refueling location which together cover 92,15% of the total flow at the cost of an initial investment of €6,613,950 and yearly losses of €310,863 that need to be covered by governments. TTS locations are more flexible and therefore cover more flow than their PTS counterparts. When discussing the results with experts in the maritime transport area this solution seems fitting. Refueling trucks have been used with success before, for example with LNG. Trucks carrying hydrogen already are in use in the region. Manufacturing trucks in a way that they are capable of refueling ships is realistic by 2030. By maximizing availability more ship owners potentially make the switch to hydrogen as fuel, due to the technical barrier of availability not being a large problem anymore.

For 2040 and 2050, however, it is no longer expected to be necessary to receive aid from the government. The demand for hydrogen is expected to make refueling locations profitable when placed optimally. The model gave an optimal solution for the years 2040 and 2050. In 2040, eight normal refueling locations are placed with 94,15% coverage. With a yearly profit of €1.318.422,- the initial starting costs of €6.276.000,- can be earned back in under five years. To ensure high profit a transition between 2030 and 2040 has to be made from TTS locations to PTS locations. The advantage of TTS locations, being able to cover a larger service area, no longer holds up when demand is bigger. The operational costs grow significantly. When comparing a situation with TTS locations with a situation without TTS locations, a reduction in operational costs of 22% is realized, doubling the yearly profits of the refueling network. In 2050, nine refueling locations are placed in the optimal situation for 89.97% coverage and a buyback period of 0,73 years to earn back the initial costs, being €5.369.738,-. The buyback periods for the situation in 2040 and 2050 are presumably lower than given as output by the model, due to already existing refueling infrastructure from earlier scenarios. From discussing the results with companies, these results seemed realistic, although the profit margin on purchasing and selling hydrogen in 2050 might be too high. This margin depends on how the prices of competition develop and what the market position of hydrogen will be. A sensitivity analysis for the scenario of 2040 reveals that a decreasing margin in hydrogen prices leads to less refueling locations being placed and significantly reduced profits.

6.2. Technological barriers

Three main technological barriers were identified in the theoretical background, the current stance of maritime hydrogen technologies, the difficulty to transfer large amounts of hydrogen into a ship at once, and the lack of a refueling network. From interviews, it became clear that the technologies are not expected to be the problem in the transition. There already are possibilities to retrofit or build a ship on hydrogen. There are challenges to overcome, such as storage size and safety guarantees, but it is expected that this will not be a limiting factor. A significant number of pilots/experiments are coordinated in Europe to gather knowledge on the construction and usage of hydrogen ships.

Innovations are necessary and expected to fill large quantities of hydrogen into a ship at once. Experimenting with refueling is not yet possible to do on a large scale due to stringent storage size regulation. A possible solution to fill significantly faster, from an interview, is to have storage tanks that are interchanged for full ones at a refueling location. Calculations by a vessel owner were made and with the current technologies, his ship would need six hours to fill. This is too much time in a profit-driven industry and incentivizes innovations to speed up refueling.

For the third identified technological barrier, the lack of a refueling network, this research developed a roadmap to place the refueling network. The current problem for vessel owners is that deciding to retrofit or build a hydrogen-fueled ship limits the possibilities of the ship significantly. Only certain routes will be available in the short term, given the political/legal barriers are solved. From discussing the results it is evident that this has mixed consequences for vessel owners. For vessel owners with long-term contracts and fixed routes hydrogen can be an early option if it is possible to refuel within the route. For vessel owners that operate on a spot market, however, switching to hydrogen early might limit the vessel too much, resulting in fewer orders.

6.3. Economic barriers

Three economic barriers identified in the literature are the lack of funding for large investments, the price and scarcity of green hydrogen, and the competition with other fuel types. From the results of this research, the first economic barrier can be considered extremely important. In the first milestone of the roadmap, 2030, significant governmental aid is needed to start and maintain a refueling network. Various funding subsidies already are present, but more are essential to achieve a successful refueling network.

The price and scarcity of green hydrogen will be a limiting factor to the success of the transition to a hydrogen-fueled inland cargo shipping industry. At this point all hydrogen projects have a hydrogen source determined in an early stage in the project, due to availability insecurities. When green hydrogen remains scarce, the price will be high. High fuel prices will scare away potential hydrogen vessel owners since fuel is the main driver for costs in the inland cargo shipping industry, which was emphasized in multiple interviews. A possible solution to this, from the theoretical background, is to make hydrogen refueling locations self-sufficient (Pereira Micena, et al., 2020). This significantly increases the initial costs to place a refueling location, but can lower operational costs and dependency on hydrogen supply.

The third economic barrier, regarding competition in the fuel market, will determine how large the market share for hydrogen-fueled ships will be. From interviews becomes evident that conventional fuel types are expected to have tariffs or limiting regulation in the future, making them less attractive. From discussing results with companies, the competitive position of fossilized fuel types might be worse due to possible legislation that might come. It could be possible that in the future vessels on fossilized fuel types will not be allowed to travel through certain areas or cities. LNG is expected to play a significant role in the transition, but as an intermediary fuel type between diesel and hydrogen, since LNG is more sustainable, but not carbon neutral. From discussing results an interesting view on this originated. It is necessary to keep the period in which LNG ships are a better alternative to hydrogen as short as possible, since ships are built for use of longer periods of 15-30 years. The sooner hydrogen becomes more attractive than LNG, the faster the transition to a carbon-neutral inland cargo shipping industry will be. The position of competing fuel types in the market influences the price margin refueling locations can earn on hydrogen. A sensitivity analysis on the difference between the purchase and selling price of hydrogen revealed that this influences both the amount of refueling locations that can be placed with profit and the total profit that can be made. A new and better sustainable fuel type may be developed and take in the expected place of hydrogen.

6.4. Political/Legal barriers

Two main political/legal barriers identified in the theoretical background are the public view on hydrogen and hydrogen regulation. The public view on hydrogen is heavily dependent on the stance of the government on the energy transition. When governments want to move away from fossilized fuels, it needs to support both moral considerations and the self-interest of the public by adopting certain policies. If the public view is on the same line the transition will speed up significantly. An interesting point brought up during the discussion of results with a company is that this stance on the transition towards hydrogen needs to be similar in multiple countries, when working in an international area, such as in this case study. When, for example, the transition in the Netherlands is in a further stage it is possible that hydrogen-fueled ships are not able to refuel in Germany yet due to political ambiguity. This would hinder some vessel owners. It is important to take steps in the transition internationally at a similar pace when operating in international areas.

For the second political/legal barrier, regarding hydrogen regulation, there are similarities to political ambiguity. Political ambiguity could lead to situations with legal ambiguity, in which hydrogen ships are allowed to ship goods in one country, while they are not in others. The antecedent for this is the lack of regulation for hydrogen as fuel in the inland cargo shipping sector. There are regulations to take into account, such as HySafe for safety measurements, HyLAW for the safe usage and bunkering of hydrogen, and the ADN for the carriage of dangerous goods over inland waterways. These regulations, however, are not designed for the usage of hydrogen for inland cargo ships. Due to hydrogen in maritime transport being very new, regulation still has to be made and permits are given at a slow pace, due to missing knowledge (Xu, et al., 2020). Some current issues with regulations are that hydrogen cargo ships are not allowed at this moment, the maximum size of hydrogen storage is not large enough to support large refueling locations and the use of hydrogen as fuel falls under the regulation of transporting hydrogen as cargo in the ADN. Especially in the first milestone of the roadmap, 2030, this will be a significant barrier. Current experiments with hydrogen cargo vessels are allowed to be used as an exemption for scientific purposes. Regulations are being formed based on these experiments and experiences. For later milestones in the roadmap, regulation is expected to be present.

6.5. Managerial implications

From the results and discussion, managerial implications can be derived. Firstly, from a governmental point of view, it is essential to support the transition towards hydrogen-fueled cargo ships with subsidies, international collaboration, and accommodating regulation. Failing to do so will result in a slower transition. Especially a proactive approach in the first step of creating a refueling network is essential, since the results of this research indicate that it is impossible to start a refueling network in 2030 without governmental aid. From the owners of refueling locations, flexibility is required. At first, TTS is the most interesting option due to high coverage, which will start to become less attractive as demand and operational costs become higher in 2040. In 2050 some owners will need to make the transition to a fast refueling speed location. Vessel owners have a tough decision to make when it is time to build or retrofit a ship. Switching to hydrogen early might be a good idea for the future, but there are significant barriers to overcome early. Since a ship is built or retrofitted to be used for a period of 15-30 years a decision has heavy consequences. Serious negative downsides to take into account early on in the transition are a lack of refueling locations and legislation.

7. CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH

7.1. Conclusion

The role of hydrogen in maritime transport is uncertain and relatively unexplored in literature. Steps need to be taken to reach environmental goals from international organizations and governments. Hydrogen can have a significant role to reach these goals. This research fills the gap in the literature on how a hydrogen refueling network should look like during the transition from fossilized fuel types towards hydrogen by performing a case study. The literature was explored to identify a model that can be used for hydrogen-fueled inland cargo vessels and identify economical, technical, and political/legal barriers that have to be taken into account. The model from Ursavas et al. (2020) was adapted to be implemented for hydrogen vessels instead of LNG vessels. This model was used in the case study and gave results on the optimal hydrogen refueling network for 2030, 2040, and 2050. Based on the results and interviews a roadmap to 2050 is created that shows how the refueling network should look like at certain timestamps. In the discussion, this is compared to the literature and earlier identified barriers.

7.2. Limitations

Within this research, limitations should be taken into account that can influence the results.

This case study has a specific scope that influences the results. The suggested refueling network only covers the flow within this scope, while this is not all flow that comes to and from, for example, Rotterdam. Other river networks influence the demand for certain areas significantly.

This research only focuses on the inland cargo ships modality. It does not take other transport modalities that also need hydrogen as fuel into account, such as other types of ships or trucks that often transport goods from ports. This can influence the results.

In this research, it is not possible to refuel during a trip due to simplification purposes and preferences of vessel owners to refuel at origin or destination. This makes some routes that travel close to a refueling location appear as not covered by refueling locations, while in reality vessels traversing those

7.3. Future research

From this research questions arise that can be the basis for follow-up research.

Where this study mostly focuses on the refueling network design, there are a high amount of uncertainties regarding the technical aspects of hydrogen as fuel. In-depth studies on how refueling can be done optimally are necessary.

One follow-up study recommended is looking into refueling locations for multiple transport modalities, such as multiple types of ships and trucks. This way possibly more demand can be generated for the location, making it require less help from governments and speeding up the transition.

Another follow-up study that needs to be done is a case study covering Europe. Inland cargo routes such as the Rhine, Maas, and Waal influence the viability of refueling locations significantly. By taking the whole of Europe as the area of interest instead, a better overview of the total flow can be given.

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