INFRASTRUCTURE DEVELOPMENT FOR GREEN HYDROGEN USE IN RAILWAY TRANSPORT – A CASE STUDY IN THE NORTHERN NETHERLANDS

Frank Hagedoorn, Evrim Ursavas, Nicky van Foreest

1. INTRODUCTION

A strong reduction of GHG emissions is required to meet the goals stated in the Paris climate agreement and to limit the impact of global warming (United Nations, 2016). While the European railway industry has already cut emissions in half since 1990, approximately 75% of trains worldwide are still diesel-fueled (European Environment Agency, 2018; Kumar & Bierlaire, 2015). Current improvements were achieved by electrification of railways and increased efficiency in diesel-fueled trains (Kumar & Bierlaire, 2015). However, the use of green hydrogen in railways may be a more promising option. Besides emission-free transport, trains running on hydrogen do not need a connection with catenaries and therefore have the benefits of more flexibility and lower infrastructure costs comparable with diesel-fueled trains (Marin, et al., 2010).

However, the high costs and lacking infrastructure hinder broad adoption of hydrogen as of today (Yavuz & Capar, 2017; Hosseini & MirHassani, 2015). These factors prevent companies from opting for hydrogen. As a result, demand is insufficient for the industry to create a complete and cost-efficient infrastructure. The Dutch government stimulates developments with several subsidies and funds to solve this.

Another drawback is that hydrogen refueling stations have to abide strict storage regulations. Current regulations are mainly based on its use as an industrial gas and as a raw material for chemistry as hydrogen has been used in this industry for a lengthier period. As a result, the rules for the use of hydrogen in new applications can be relatively strict or are not (yet) sufficient (HyLaw, 2018).

To prepare the industry for future hydrogen demand, it is important to design a cost-efficient hydrogen railway network. Trains follow predefined routes, hence fuel demand can be seen as a flow from origin to destination (O-D). Flow-interception location models (FILM) are used to locate facilities based on demand flow. The flow refueling location model (FRLM) and the flow capturing location model (FCLM) belong to this category of models and are commonly used for alternative fuels. Railways have clear O-D data, which makes it excellent to use for the FRLM (Kuby & Lim, 2005; Tanaka, et al., 2019). Upchurch et al. (2009) extended the FRLM model by including capacity of a fuel station (CFRLM). This extension is useful in this context as HRSs have to abide strict rules and regulations regarding storage amount and safety distances as hydrogen falls in a different category than fossil fuels (Rose, et al., 2020; Sun, et al., 2014; IRENA, 2020).

No research exists on HRS infrastructure for trains yet (Rose, et al., 2020). Current research on alternative fuel station infrastructure dominates road transport (Rose, et al., 2020; Liu, et al., 2019). However, there are significant differences in the use of alternative fuels for road transport and trains; for example, in terms of infrastructure, total cost of ownership (TCO), and technological requirements. This contains among others safety regulations, fuel consumption, range, weight, and storage capacities of the vehicle (Bongartz, et al., 2018; Kluschke, et al., 2019). Besides, Kluschke et al. (2019) recommended further research to take energy supply and infrastructure development into account as input parameters for modelling.

The European Union set up a pilot in the Northern Netherlands to address the requirements for a fully-integrated and functioning “hydrogen valley” (European Commission, 2021). The HEAVENN project uses hydrogen that is produced from abundant local renewable energy sources to decarbonize sectors like heat, industry, and transportation. The goal is to create a hydrogen economy that covers the entire chain from production to the end-use of hydrogen, which could serve as a blueprint for global implementation (European Commission, 2021). This study will focus on the transportation sector part of the HEAVENN project and specifically the railway industry.

The Dutch railway network is used to conduct a case study. The Dutch railway network consists of over 3200 km of railway lines, of which more than 75 percent are electrified (CBS, 2018). The provinces of Groningen, Friesland, Overijssel, and Gelderland are the four provinces having unelectrified railway lines, which make the Northern Netherlands an interesting region to implement the use of hydrogen as a fuel. A feasibility study in Groningen showed that hydrogen trains can be a fully-fledged sustainable alternative to the current diesel trains (Provincie Groningen, 2020).

Therefore, Groningen wants to start using passenger trains powered by hydrogen from 2024 onwards.

The main research question is: ‘’What are the optimal locations for hydrogen refuel stations to achieve a cost-efficient hydrogen railway network?”. To answer this, the CFRLM is reformulated to incorporate hydrogen and railway-specific aspects relating to fuel cell efficiency, train range, hydrogen supply costs, and hydrogen price. Real-life data will be used to execute different scenarios. The study uses railway data that consists of all trips on unelectrified lines in the Northern Netherlands. The scenario for 2030 includes the 4 hydrogen trains ordered, while the scenarios for 2040 and 2050 cover all trains in the Northern Netherlands to be replaced by hydrogen trains. Besides, the scenarios incorporate developments in the field of hydrogen consumption rate, distribution costs, train range, and hydrogen price. Therewith, this study contributes to the development of a hydrogen economy in the Northern Netherlands. Governments and train companies can use the developed model and implications of this research to plan the development of future HRSs for railway transport.

In the next section, the theoretical background will be explored. Then, the mathematical model and the case study will be described. Thereafter, the results of this study will be presented and are discussed in the section afterwards. The report ends with a conclusion where limitations and possibilities for further research will be mentioned as well.

2. THEORETICAL BACKGROUND

In this section, the relevant literature will be described to obtain a more detailed view on the application of hydrogen in railways, constraints and barriers, and infrastructure development. This helps to understand the feasibility of a hydrogen railway network in the Netherlands and factors that influence the development of such a network.

2.1. Hydrogen in railways

Adoption of hydrogen in railways is low as of today. Currently, mainly pilots and tests are being carried out to test the feasibility of hydrogen trains. These have shown that “hydrogen trains are most appropriate for long and relatively low-frequency routes, with short downtimes and limited time for battery charging, and routes not already electrified” (Hydrogen Council, 2020). Hydrogen trains are already cheaper compared to catenary electric trains based on these circumstances. In comparison to diesel-fueled trains, hydrogen in railways is expected to be cheaper with a carbon price of 120 euros per ton CO2, dependent on region-specific factors such as hydrogen and diesel price (Hydrogen Council, 2020).

Relating to the development costs of a hydrogen infrastructure, Kuby & Lim (2005) noticed that the costs of a hydrogen refueling infrastructure for trains would be much cheaper than a similar kind of infrastructure for the automotive industry. They state that the rail network offers fewer path miles and that trains can travel longer distances due to more fuel storage capacity. Therefore, relatively few stations are needed to cover the network in comparison to the automotive industry, resulting in lower initial investment costs. Furthermore, adoption of hydrogen in railways would foster demand, which is needed to achieve economies of scale from the supply side. This would help to bring the hydrogen price down. Therefore, railway might be an excellent application for hydrogen as it needs relatively little investment costs and helps to decrease the price of hydrogen. This is important as a lower hydrogen price could trigger adoption among multiple applications (Kuby & Lim, 2005).

FCH JU (2019) and Langshaw et al. (2020) indicated the effect of economies of scale on the TCO of an HRS. FCH JU (2019) mentions CAPEX of 4.2 million euros for an HRS with a daily capacity of 1,500 kg hydrogen. Doubling daily capacity to 3,000 kg, the costs of an HRS add up to 7.8 million euros, an increase of 84%. An HRS with a daily capacity of 6,000 kg hydrogen leads to costs of 12.6 million euros, an increase of 61%. Hence, larger HRSs have a positive effect on TCO. Arcadis (2016) calculated the costs of building HRSs in the Northern Netherlands. They mentioned building costs of 25 million euros for an HRS in Groningen with a daily capacity of 8,000 kg and 10 million euros for one in Leeuwarden with a daily capacity of 3,000 kg. So, the actual investment costs for HRSs in the Northern Netherlands are higher, but the calculation indicates the effect of economies of scale.

As for the cost of the railway infrastructure itself, the use of hydrogen as a fuel in railways would also save governments significant investment in the rail network. Trains running on hydrogen do not need a connection with catenaries, hence adoption of hydrogen in railways would make the building of catenaries over the approximate 1,000 km of non-electrified railway lines in the Netherlands superfluous. Around 100 diesel-fueled trains run on these non-electrified lines per day (Engie, 2020). Most non-electrified railway lines are located in the north and east of the Netherlands. Hence, these lines are very useful in this study and are related to the HEAVENN project. According to El-Sayed Al-Tony & Lashine (2000), the costs of catenaries vary from $800,000 to $2,000,000 per km, which indicates the amount of money concerned with railway infrastructure decisions. The provinces of Friesland and Groningen have commissioned research into the costs of electrification of diesel-fueled railway lines in the Northern Netherlands. The report showed investment costs of 593 million euros, with a payback period of more than 100 years (Ricardo Rail, 2016). Therefore, the use of hydrogen as a fuel in railways should be a priority for these non-electrified lines.

Looking at the wider application of hydrogen trains, it is not necessary to remove existing catenaries for use of hydrogen trains. Namely, an international European consortium within the FCH2RAIL EU project is working on the development of a new train that uses catenaries, but this can also run on a fuel cell (Waterstof Magazine, 2020a). The core of the project is a hybrid bi-modal propulsion system that combines the electrical power supply from the catenary with a 'hybrid fuel cell power pack' consisting of fuel cells and batteries. Where no catenary is available, the fuel cell takes over the energy supply. Another option is battery-electric trains, but they have a limited range of 30 to 70 km, largely dependent on the route profile and temperature (Waterstof Magazine, 2020a). Hence, battery-electric trains are most appropriate for short routes with partial electrification.

Looking at the Dutch railway network, approximately 2,200 km of railway lines are electrified (see figure 1). The NS uses around 1.2 TWh of electricity per year to run their trains, generated from renewable wind energy (NS, 2018). In comparison with hydrogen, this 1.2 TWh of electricity could be used to produce 24 million kg of hydrogen assuming that one kg of hydrogen needs 50 KWh (Al-Gahtani, et al., 2021). Using a fuel consumption of 0.25 kg per km, this means that trains could drive 96 million km on hydrogen, which is already a significant part of the 165 million km Dutch trains drove in 2019 (FCH2 JU, 2017; ProRail, 2020). However, an additional 17.25 million kg hydrogen is needed to fuel the remaining 69 million km for 2019. This indicates that electric trains using catenaries are more efficient as of today. However, developments in among others electrolyser efficiency would lower the additional hydrogen needed and its corresponding costs. This could ultimately make the costs per km competitive to electrified trains, or even cheaper. In addition, adoption of hydrogen saves high investment costs in the railway network as indicated earlier.

Figure 1: Railway lines in the Netherlands (Andrews, 2017)

On the other hand, the Dutch government states that hydrogen should mainly be used for applications where no alternatives, such as electrification, are present (Gasunie, 2021). Thus, current policies prioritize the use of hydrogen for use cases such as steel production, chemical production, and as a fuel for transportation modes that are difficult to electrify. This could mean that the use of hydrogen in trains could be limited for the near future. On the other hand, the government fosters tests and pilots for other applications, such as railways.

2.2. Technical & economic constraints and barriers

As mentioned before, the high costs associated with hydrogen are the main barrier to adoption as of today. Al-Gahtani et al. (2021) mention that the levelized cost of hydrogen (LCOH) is mainly dependent on capacity, the costs of electricity, and the costs of electrolysers. A price of less than $2/kg is needed to make hydrogen competitive with diesel (Reddi, et al., 2017). Current methods that can produce hydrogen at $2/kg are gasification techniques and steam reforming. However, these methods produce so-called ‘grey hydrogen’ as these methods emit CO2 during production. Furthermore, the produced hydrogen is not suited for application in fuel cells, as hydrogen-powered vehicles require a purity level of 99.97% and these methods can only reach purity levels of 97.5% (ISO 14687, 2019). This means, the hydrogen contains too high values of elements such as CO_2, CO, S, and H_2O. The sum of impurities for application in fuel cells is not allowed to exceed 300 μmol/mol (ISO 14687, 2019).

Another method to produce hydrogen is electrolysis. This method produces emission-free hydrogen, or ‘green hydrogen’, and complies with the required purity level stated in ISO 14687 (2019). However, this method has the disadvantage of higher production costs, currently in the region of $4/kg to $6/kg (Reddi, et al., 2017). The cost of green hydrogen can be reduced to $2/kg, but this requires several developments. A decrease of renewable energy costs to $20-$30/MWh, currently in the region of $60/MWh depending on the energy source and location, and a significant reduction in the costs of electrolysers would have the greatest impact on the costs (Edwardes-Evans, 2020; IRENA, 2020). Other developments that can reduce hydrogen costs are an increase in electrolyser efficiency, extra load hours, increased lifetime of electrolysers, and a lower interest rate (see figure 2).

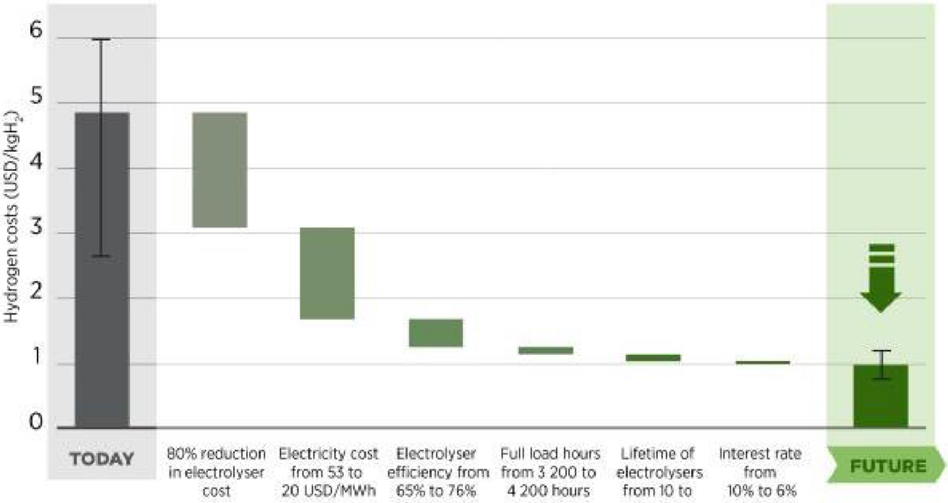


Figure 2: The journey to a competitive green hydrogen (IRENA, 2020)

In addition to the need for developments regarding the price of hydrogen, many legal aspects need to be arranged as well. Regulations regarding the use of hydrogen in new applications, such as trains, are relatively strict or insufficient. This is because hydrogen is legally classified in the same category as natural gas and gasoline. Thereby, hydrogen is subject to health and environmental risks and fire and explosion hazards (HyLaw, 2018). For this reason, HRSs must adhere to risk assessments, safety requirements, and safety distances. This includes strict storage regulations that prescribe the allowable amount and pressure level of hydrogen (Rose, et al., 2020). Subsequent to that, HyLaw (2018) states that: “Hydrogen is legally classified as dangerous to transport and is included in the list of dangerous goods in Annex A concerning the International Carriage of Dangerous Goods by Road (ADR)”. As a result, hydrogen trailers are not allowed to drive through tunnels, for example.

In addition, Sun et al. (2014) state that the storage location has to follow strict rules and regulations regarding the distance between different hydrogen equipment. Fuel stations that want to provide hydrogen have to apply for a permit and comply with PGS 35 that states location-specific rules regarding storage amount and distances (IRENA, 2020). Nonetheless, hydrogen refueling should generally be allowed on land where conventional refueling stations are in use (HyLaw, 2018). On-site production of hydrogen is less convenient, as this activity is currently only allowed in industrial zones. Hence, this is important to take into account for potential HRS locations.

Due to the limited experience with hydrogen in new applications, authorities exert a high level of precaution (HyLaw, 2018). However, current laws and regulations are considered to be unreasonably high. Research from Sun et al. (2014) highlighted the risks associated with hydrogen refueling. They state that the overall chance of a fatal accident during refueling is far below the acceptance level of customers. Therefore, indicating that current regulations might indeed be too strict. They mention three main risks, to be: leakage from booster compressors with a probability of 69%, followed by leakage from tube storages with 27%, and bore rupture of pipes with a probability of about 4% (Sun, et al., 2014).

Current regulations allow hydrogen storage for light-duty vehicles (LDVs), such as cars, at 700 bar, while hydrogen for heavy-duty vehicles (HDVs), which includes trains, is stored at 350 bar (IRENA, 2020). Differences in storage pressure affect both safety distances and storage amount allowed (Sun, et al., 2014). For example, a higher storage pressure means that more hydrogen can be stored in a tank, but also requires more safety distance. As a result, fewer hydrogen modules can be stored at an HRS per km^2. On the other hand, more hydrogen can be stored in a tank due to the higher density of hydrogen molecules. So, fewer modules are needed to refuel a certain number of trains. Furthermore, storage pressure influences compression efficiency. According to IRENA (2020), hydrogen compressed at 350 bar results in a compression loss of 10% to 11%, while storage at 700 bar results in a compression loss of 15% to 16%.

Apart from hydrogen production methods, price developments, and laws and regulations, another important aspect is the distribution of hydrogen from an electrolysis facility to an HRS. Reuss et al. (2019) evaluated technical and economic decisions to achieve an optimal hydrogen supply chain in Germany. They state that the distribution of hydrogen is most efficient with gaseous compressed trucks in case of short distances and low demand, whereas pipelines have shown to be more efficient for areas with high demand. As demand is expected to remain relatively low in the near future, trucks might be the most used distribution option for short-term scenarios, while increasing use of pipelines is expected in more long-term future scenarios. This distribution strategy is in line with the distribution strategy that Company D expressed. They expressed their focus on supplying hydrogen to locations within 100 km of the plant. Because of this relatively small range, Company D focuses on distribution with trailers and containers instead of pipelines. They have 3 trailers that can transport 500 kg of hydrogen each and mention transport costs of € 1,00/km for a one-way trip. So, transport costs are dependent on occupancy rate of the truck. Hence, the distance from a hydrogen plant to a potential HRS influences the optimal HRS location decision.

Lastly, Apostolou & Xydis (2019) mention that the HRS network and number of hydrogen-fueled vehicles should be developed simultaneously. To achieve this, the Dutch government has several arrangements aiming to stimulate both HRS infrastructure development and the use of hydrogen vehicles. For example, SNN, which provides a subsidy of at least €100,000 for projects to develop promising innovative products or services with market potential, aimed at building and testing prototypes. In addition, fiscal arrangements exist like investment allowances for investments in energy-saving equipment and sustainable energy (EIA) and environmentally friendly operating assets (MIA). These subsidies and funds should help encourage adoption of hydrogen. Also the EU has granted several subsidies and funds to stimulate developments: 2.8 billion euros will be invested in projects related to HEAVENN, of which 90 million euros specifically for the creation of a hydrogen economy in the Northern Netherlands (TOPDUTCH, 2020).

2.3. Infrastructure development

The Netherlands has expressed the goal to have 4 GW of electrolyser capacity and 11 GW of offshore wind capacity installed to upscale hydrogen production by 2030 (FME, et al., 2021). Although this is a good start for the development of a hydrogen economy, it is expected that the Netherlands will not be able to generate enough sustainable energy necessary to meet future green hydrogen demand. Namely, the Dutch weather conditions are not favourable for generating sufficient wind and solar energy. Therefore, the Dutch government expects to be a net importer of green hydrogen by 2050 (Gasunie, 2021). Though, they state the goal to create a hydrogen hub and become a leading country in hydrogen. The aim is to develop a hydrogen backbone that consists of 1,400 km of pipelines by 2030 (FME, et al., 2021). This backbone will connect the overall pipeline network, which already has over 1,000 km of hydrogen pipelines. Even more, the Netherlands has one of the most extensive natural gas grids, consisting of 136,000 km of pipelines. These pipelines will be connected and adapted to the hydrogen network while national gas usage is being phased out (FME, et al., 2021).

Ultimately, these pipelines could be connected to HRSs. GldH2, the first hydrogen cooperation in the Netherlands, is leading such a case study. They want to build an underground hydrogen network in Zutphen, where an electrolyser on De Mars industrial area will be the starting point of a hydrogen ring pipeline (Waterstof Magazine, 2020b). The hydrogen pipeline passes the Prorail shunting yard and a branch of the hydrogen pipeline could permanently provide CO_2-free hydrogen at the shunting yard (Waterstof Magazine, 2020b). If similar cases are developed in the Northern Netherlands, this could decrease distribution costs and ease supply of hydrogen by lowering pressure on capacity restrictions of an HRS. However, optimal locations for HRSs should be determined first.

Regarding the optimal locations for an HRS, Hosseini & Mirhassani (2015) and Capar et al. (2013) mention that the success of hydrogen as a fuel is dependent on the ability to provide a comprehensively covered refueling station network with a cost-efficient infrastructure. Additionally, Lin et al. (2020) state that selecting the location is a key decision for long-term performance of the station as it influences cost, efficiency, and quality of refueling. Therefore, the development of a hydrogen infrastructure is vital for the success of hydrogen as a fuel. Current literature presents multiple approaches to build this infrastructure. Studies can be classified based on the type of mobility, fuel type, model used, and extensions used like the inclusion of capacity restrictions, effect of policy, infrastructure development, and energy supply.

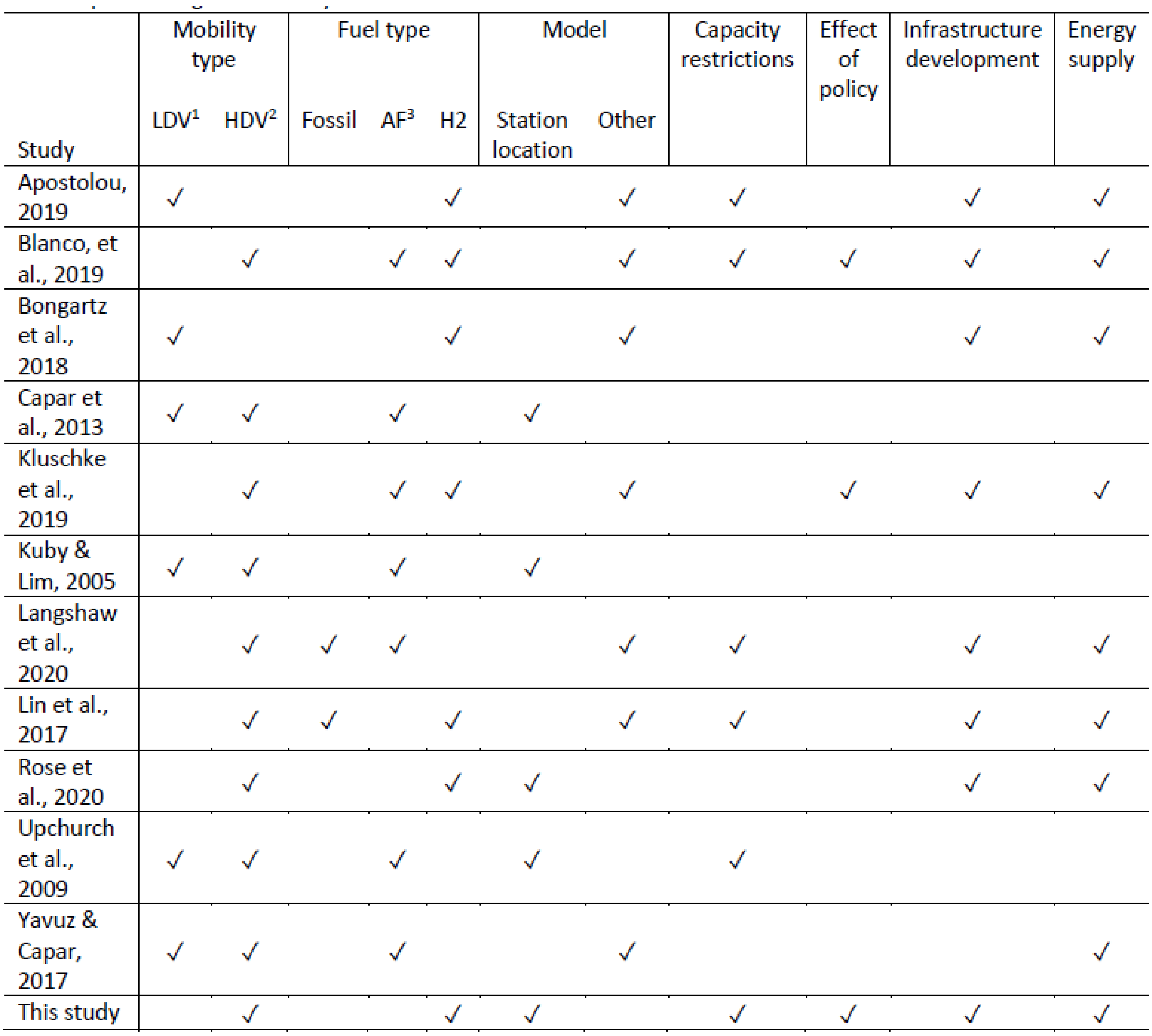
Lin et al. (2020) presented an overview of different models that are widely used for determining station locations. They distinguish different models based on the structure of the area and spatial dimensions of stations. Research from Yavuz & Capar (2017) used path- or node-based models to categorize the different models.

The p-median model, p-center model, and covering model (set covering and maximal covering location) are considered to be the basic models to locate a facility or station (Lin, et al., 2020). The p-median model is developed by Hakimi (1964) and minimizes the travel distance from a demand point to a station. Nicholas & Ogden (2006) used this model to locate hydrogen refuel stations in California. The p-center model, on the other hand, minimizes the maximum distance to a station (Lin, et al., 2020). The goal of the set covering model is to use as few stations as possible while assuring that vehicles do not run out of fuel during a trip (Wang & Lin, 2009). The maximal covering location model uses a fixed number of stations to be built and maximizes covered demand. Church & ReVelle (1974) used this model to locate emergency service facilities.

For alternative fuel stations, flow-intercepting models are more appropriate. The flow refueling location model (FRLM) and the flow capturing location model (FCLM) belong to this category of models. These models are used to determine station locations based on demand flow. This means that the optimal location for a station is where the captured flow is maximized. Tanaka et al. (2019) used a flow-interception location model (FILM) for finding the optimal locations for public libraries at railway stations to maximize profit. Horner & Groves (2007) used FILM to identify the optimal railway stations to locate park-and-ride facilities. Both studies stressed the use of flow interception location models for railway applications relating to the clear O-D data that railways have. The basic models could be used to locate stations close to demand points or origins, but neglect destination locations. Hence, the use of FILM to include the flow between O-D is more appropriate. Though, a distinction should be made between the studies of Tanaka et al. (2019) and Horner & Groves (2007) and the objective of this study. Those studies aim to maximize profit of a facility and therefore maximize the flow captured. Both studies include the possibility of capturing a flow at both origin and destination stations. However, for refueling decisions, it is imperative to know at which station a train will be refueled, as the amount of hydrogen must be available.

The difference between FRLM and FCLM is that the FRLM takes the opportunity for a vehicle to refuel during a trip into account (Kuby & Lim, 2005). However, trains cannot refuel during a trip as they have to refuel at specific marshalling yards, outside the timetable. Upchurch et al. (2009) extended the FRLM model to take the capacity of a fuel station into account. They state that the inclusion of capacity restrictions has little influence in the beginning phase as demand is low. However, capacity restrictions become increasingly important as hydrogen adoption starts to rise. Table 1 presents an overview of past literature and shows the positioning of this study, where LDV[1], HDV[2], AF[3] is for light-duty vehicle, heavy-duty vehicle, and alternative fuels, respectively.

Table 1: Positioning of this study



Study	Mobility type		Fuel type			Model		Capacity restrictions	Effect of policy	Infrastructure development	Energy supply
	LDV[1]	HDV[2]	Fossil	AF[3]	H2	Station location	Other				
Apostolou, 2019	✓				✓		✓	✓		✓	✓
Blanco, et al., 2019		✓		✓	✓		✓	✓	✓	✓	✓
Bongartz et al., 2018	✓				✓		✓			✓	✓
Capar et al., 2013	✓	✓		✓		✓					
Kluschke et al., 2019		✓		✓	✓		✓		✓	✓	✓
Kuby & Lim, 2005	✓	✓		✓		✓					
Langshaw et al., 2020		✓	✓	✓			✓	✓		✓	✓
Lin et al., 2017		✓	✓		✓		✓	✓		✓	✓
Rose et al., 2020		✓			✓	✓				✓	✓
Upchurch et al., 2009	✓	✓		✓		✓		✓			
Yavuz & Capar, 2017	✓	✓		✓			✓				✓
This study		✓			✓	✓		✓	✓	✓	✓

In this study, a refueling station location model is formulated to prepare the railway network for future use of hydrogen as a fuel. The model is based on some generalizations and assumptions, but these are valid for most realistic situations. The assumptions are explained in the next section. This study contributes to the work from Upchurch et al. (2009) in the following dimensions. First, it extends the model from Upchurch et al. (2009) by including distribution costs from an electrolysis facility to a potential HRS. Second, the captured flow is allocated to the HRS with the lowest distribution costs to achieve a cost-efficient hydrogen railway network. In addition, this prevents a flow from being double captured, resulting in more accurate calculations for the amount of hydrogen needed. Third, the amount of hydrogen and the daily capacity of an HRS needed are calculated for different levels of hydrogen flow. The corresponding costs are based on estimations as many uncertainties exist as of today but can be used as an indication. Lastly, this study creates three future scenarios that can be used to gain insight into the implementation of hydrogen in the Northern Netherlands. The scenarios cover 4 hydrogen trains replacing 4 diesel-fueled trains for 2030, and all diesel-fueled trains to be replaced from 2040 onwards. Additionally, the effect of developments regarding hydrogen consumption rate, range of a train, distribution costs, and hydrogen price is investigated.

Therewith, this study contributes to the development of a hydrogen economy in the Northern Netherlands. The implications of this research can be used for the development of a hydrogen railway infrastructure for railway transport and potential application in other countries or other modalities.

3. MODEL DESCRIPTION

In this section, the model will be explained. First, assumptions that underlie this research are motivated followed by the decision variables, sets, and parameters used. Afterwards, the objective function is outlined to present the goal of the model and its constraints. Lastly, the acquisition of data and model solving processes are explained.

3.1. Problem description

This study aims to calculate the optimal locations for HRSs for different levels of hydrogen used by trains. Therefore, the objective function tries to maximize the amount of flow captured by an HRS. The flow is calculated by multiplying the frequency of a trip by the travel distance on that specific path. To calculate the optimal locations for HRSs, it is imperative to decide upon potential HRS locations. Hydrogen refuel pumps cannot be placed at existing railway stations, but have to be at specific marshalling yards. These areas are located near the most important railway stations, likewise the origin or destination stations of trips. Therefore, possible HRSs should only be located at O-D stations where a marshalling yard exists (see Figure 3). Even more, it is not possible to refuel a train during a trip as trains have to be refueled outside the regular timetable.

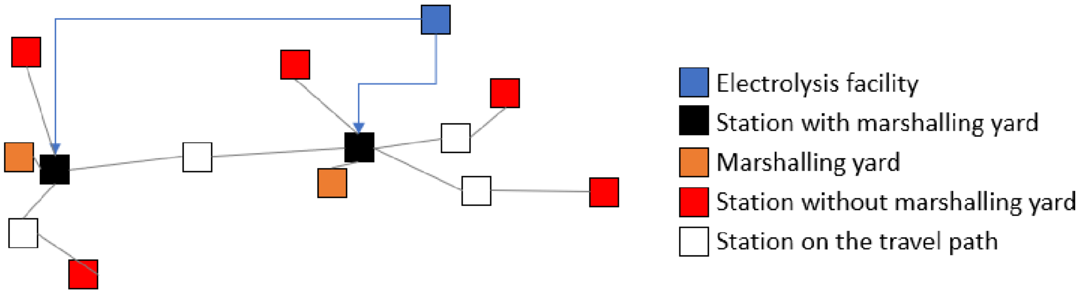


Figure 3: Example of a railway network

3.2. Mathematical model

Assumptions

Several assumptions underlie this research. First, it is assumed that all trains have equal hydrogen tank size and hydrogen consumption rate. This assumption makes it possible to measure the distance equivalent per kg hydrogen remaining in the tank.

Second, the capacity of a refueling station is not dependent on refuel time and waiting time in this study, similar to research from (Hosseini & MirHassani, 2015). Trains are refueled during off-peak hours or when taken over by a refueled train, similar to refueling management for diesel-fueled trains.

Third, the influence of weather conditions is excluded in this research. Kumar & Bierlaire (2015) stressed further research to incorporate the effect of weather conditions on train range, however, it is neglected in this study for simplicity reasons. Conservative ranges are chosen for the different scenarios to achieve weather-resistant and realistic results.

Fourth, it is assumed that trains are bound to specific travel paths. This assumption makes it possible to calculate the moment of refueling based on completing a fixed number of trips. Continuous changing travel paths would make refueling management planning more difficult.

Lastly, it is assumed that HRSs are always accessible for refueling, therefore excluding variable v_h from Upchurch et al. (2009) which is used to indicate whether a facility is open or closed. Refueling of trains is taken into account when drawing up the timetable. Railway companies organize refueling accordingly.

Decision variables

The objective of this study is to find the optimal locations for HRSs. To achieve this, an HRS should cover as much flow as possible. Hence, the goal is to maximize the amount of flow (f_q), that is captured by an HRS (y_q). The amount of flow captured (f_q) is calculated by newly added formulas using D_{ki}, D_{kj}, DD_{ki}, and DD_{kj}, as presented in Appendix 6A. These variables help to distinguish the flow captured by an origin station or destination station and allocate served demand accordingly.

f_q	the flow between each O–D pair q
y_q	binary variable; value of 1 if an HRS can refuel trip q, 0 otherwise
x_k	binary variable; value of 1 if a facility is located at k, 0 otherwise
D_{ki}	demand served by HRS at location k, at origin i
D_{kj}	demand served by HRS at location k, at destination j
DD_{ki}	demand captured by HRS at location k, at origin i
DD_{kj}	demand captured by HRS at location k, at destination j

Sets and parameters

This research applied sets and parameters used in the model from Upchurch et al. (2009). Also, new sets and parameters are introduced relating to calculations of demand and distribution costs. Not all parameters in the list below are included in the objective function. Some parameters represent a combination of individual parameters, as used in Appendix 6A.

Q	set of all O–D pairs
K	set of all potential HRS location
P	number of hydrogen stations to be located

The following additional parameters are introduced:

I	set of all railway stations at origin of a travel path
J	set of all railway stations at destination of a travel path
α	percentage of the total flow dedicated to hydrogen trains
Range	range of a hydrogen train (km)
$freq_q$	frequency of a trip between O-D pair q (km)
d_q	distance between origin and destination on path q (km)
d_{HRSki}	distance from origin station i with marshalling yard to HRS at location k (km)
d_{HRSkj}	distance from destination station j with marshalling yard to HRS at location k (km)
d_{HRSke}	distance from HRS at location k to electrolysis facility e (km)
CAP_k	capacity of an HRS at location k (kg per day)
DT_{km}	distribution cost from electrolyser to HRS at location k for transportation by mode m ($m = 1$ for truck, $m = 2$ pipelines, in €/km per module of 500 kg hydrogen)
CD_{ki}	distribution cost from electrolysis facility to HRS at location k at origin i of travel path (€)
CD_{kj}	distribution cost from electrolysis facility to HRS at location k at destination j of travel path (€)

Objective function

The aim of this research is to analyse the optimal locations of HRSs for different levels of hydrogen adoption in railway transport. The objective uses the CFRLM model from Upchurch et al. (2009), which is reformulated to obtain a cost-efficient HRS network. This relates to the fact that the model allocates a flow to the HRS with the lowest distribution costs if a flow is captured by both the origin and destination station. The reformulation of fq is shown in Appendix 6A.

$$max \sum_{q \in Q} f_q * y_q$$

Constraints

Constraints are utilized in this research to ensure that trains cannot run out of fuel, all hydrogen trains are captured and all hydrogen trains can be refueled by a potential HRS. A train running out of fuel would seriously impact the regular timetable. If the captured flow exceeds the capacity of a station, the additional capacity needed is calculated.

(1) $range - 2d_q \geq 0$

(2) $\sum_{q \in Q} \quad f_q * y_q \leq x_k * CAP_k$

(3) $\sum_{k \in K} \quad x_k = p$

(4) $y_q, x_k \in \{0,1\}$

(5) p integer

The objective of this study is to find the optimal locations for HRSs. An optimal location maximizes the amount of flow captured while taking the capacity of a station into account. However, the model is built such that more weight is given to the distribution distance from an electrolysis facility to an HRS, than to the capacity of an HRS. This premise improves cost-efficiency of the network.

Constraint (1) ensures that trains do not run out of fuel during a round trip. If a train cannot complete a round trip before running out of fuel, an HRS is needed at both the origin and destination station. A train is refueled during off-peak hours or while taken over by another train.

Constraint (2) ensures that the total demand allocated to an HRS is less or equal to its capacity.

Constraint (3) sets the number of HRSs to use in the simulation equal to p.

Constraint (4) sets variable y_q to a binary value, as the flow can be captured (1) or not captured (0) and sets variable x_k to a binary value, as an HRS can be located at k (1) or not (0).

Constraint (5) makes sure that the number of HRS stations to be located is an integer.

3.3. Explanation of method

Python code was used to acquire usable flow demand data. 4 different codes were built to eventually achieve data in the format of origin – destination – frequency. Next, the obtained data is put in Excel where it is used for the simulation. The model is solved through Excel Solver. The Excel Solver calculates the optimal locations for HRSs, taking the constraints into account. The model is built such that if a flow is covered by both the origin and destination, the flow is assigned to the station with the lowest distribution costs. The capacity constraints are excluded if the solver could not find a feasible solution. If this was the case, the simulation results showed the additional capacity needed in kg per day.

The excel file is extended to show insights into the data. For example, the result of the simulation not only shows how much of the flow is captured and by which station, but it also shows the amount of hydrogen needed at an HRS, the costs of the hydrogen needed, and the distribution costs of supplying the hydrogen to an HRS. However, the costs of hydrogen and an HRS are based on estimates as mentioned before, as future costs are uncertain.

4. CASE STUDY

This part of the project is devoted to the case study in the Northern Netherlands. The execution of the simulation is explained. The flow demand data used in this study consists of 18 O-D pairs, over which 126,949 trips were made. The data covers all passenger train trips over diesel-fueled lines in the Northern Netherlands from the period 20-04-2020 to 11-12-2020, hence 34 weeks of data. The data is multiplied by 52/34 to make calculations based on yearly data. The flow is calculated by multiplying the frequency of a trip by the travel distance. In total, a flow of 8,494,880 km is used in the simulation.

The distance travelled between an origin and destination given in the text files turned out to be unreliable. Therefore, the distance is looked up through Google Maps. This is not the most accurate way as the application covers road distances. However, the NS Reisplanner is used to validate the routes and transfer stations. Hence, the difference between used travel distance and actual travel distance should be minimal. The distances on specific travel paths and the distances from an HRS to the electrolyser in Delfzijl are shown in Appendix 6B.

Additionally, the distance travelled from a station with marshalling yard to the HRS is included. The total travel distance to an HRS, which is calculated by the number of times a train has to be refueled multiplied by the distance to the HRS, is added to the flow of that specific travel path. Existing locations of marshalling yards were given by NS. In the Northern Netherlands, there are marshalling yards in Groningen and Leeuwarden, which means that potential HRSs can only be located in Groningen and/or Leeuwarden. The distance from station Groningen to the marshalling yard is 4.5 km and the distance from station Leeuwarden to the marshalling yard is 1 km.

In this study, the hydrogen is assumed to be supplied at the Deltaweg. Hence, a flow from Leeuwarden to Groningen is assigned to Groningen as the distribution costs are less than those to Leeuwarden. For simplicity reasons it is assumed that the supplier can supply all future hydrogen demand, being the only supplier to potential HRSs in Groningen and Leeuwarden. Hydrogen is supplied in modules of 500 kg.

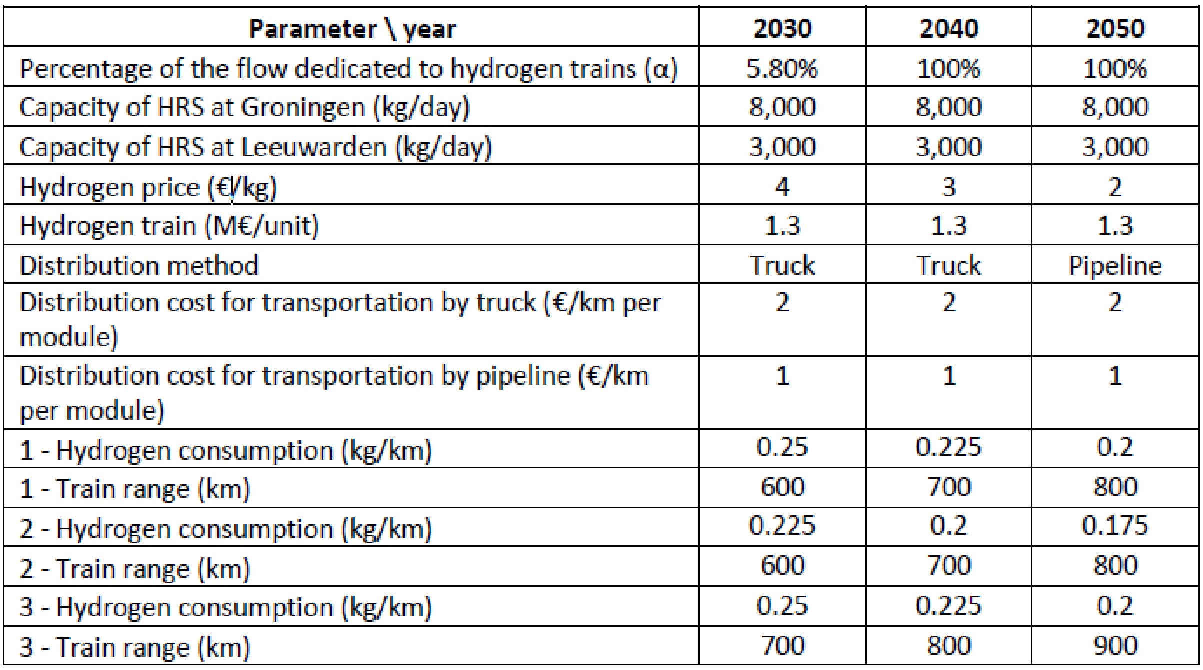
The first scenario contains the non-electrified lines in the Northern Netherlands to replace four diesel-fueled trains. Groningen has announced the purchase of 4 hydrogen trains from 2024 onwards, while 69 trains are operating in the Northern Netherlands in total. Therefore, the scenario covers 5.80% of the total flow over diesel-fueled lines in the Northern Netherlands. Namely, 4 out of 69 corresponds to 5.80% of the total flow, which is a realistic scenario for 2030. As it is expected that hydrogen use will increase in the future, the second and third scenarios cover all trains driving over the diesel-fueled lines in the Northern Netherlands. The current concessions in the Northern Netherlands expire by 2035, hence this is a realistic moment to replace diesel trains, with possibly, hydrogen trains. Therefore, a possible scenario is that 100% of the current flow is covered by hydrogen trains from 2040 onwards.

The parameter α, the percent of flow dedicated to hydrogen trains, can be changed to incorporate different levels of adoption of hydrogen in railways. α is set to 5.80% for 2030 and 100% for 2040 and 2050.

A daily capacity of 8,000 kg is used for a potential HRS in Groningen and a daily capacity of 3,000 kg for a potential HRS in Leeuwarden. A daily capacity of 8,000 kg means that an HRS can refuel 11,680,000 flow km (8,000 kg * 365 days per year * (1 / hydrogen consumption rate)). In this example, the hydrogen consumption rate is set to 0.25 kg/km. The capacities for Groningen and Leeuwarden are in line with the plans stated in the report of Arcadis (2016). The total building costs for an HRS in Groningen with a daily capacity of 8,000 kg are approximately 25 million euros (Arcadis, 2016). The building costs for an HRS with a daily capacity of 3,000 kg for Leeuwarden is around 10 million euros. Therefore, total building costs amount to approximately 35 million euros. The expected costs for the modification of electric trains are used to estimate the costs of a hydrogen train.

The parameter values listed in Table 2 are used. Developments in the future would probably be beneficial for the business case of hydrogen in railways as explained in Section 2. Developments in fuel cells could decrease the hydrogen consumption per km. Adaptations to current regulations might allow hydrogen storage at 700 bar, which means that storage capacity increases leading to a higher range achievable. The parameter values are based on the information gathered from the expert interviews. In addition, parameter values are derived from reports such as stated in Arcadis (2016), FCH JU (2019), and IRENA (2020). Each scenario includes three possible combinations of hydrogen consumption and train range. Case 1 is considered to be the base case. Case 2 tests the effect of increased efficiency in fuel cells, resulting in decreased hydrogen consumption. Case 3 tests the effect of increased train range, which could be possible if regulations allow higher storage pressure for HDVs.

Table 2: Parameter values



Parameter \ year	2030	2040	2050
Percentage of the flow dedicated to hydrogen trains (α)	5.80%	100%	100%
Capacity of HRS at Groningen (kg/day)	8,000	8,000	8,000
Capacity of HRS at Leeuwarden (kg/day)	3,000	3,000	3,000
Hydrogen price (€/kg)	4	3	2
Hydrogen train (M€/unit)	1.3	1.3	1.3
Distribution method	Truck	Truck	Pipeline
Distribution cost for transportation by truck (€/km per module)	2	2	2
Distribution cost for transportation by pipeline (€/km per module)	1	1	1
1 - Hydrogen consumption (kg/km)	0.25	0.225	0.2
1 - Train range (km)	600	700	800
2 - Hydrogen consumption (kg/km)	0.225	0.2	0.175
2 - Train range (km)	600	700	800
3 - Hydrogen consumption (kg/km)	0.25	0.225	0.2
3 - Train range (km)	700	800	900

Besides the simulation, three interviews have been executed with industry experts to gain more insights into the practical implementation of hydrogen in railways in the Northern Netherlands. The three interviewees were involved in the pilot with the hydrogen train in Groningen in 2020 and monitor developments regarding hydrogen and the railway sector.

5. RESULTS

This section shows the results of the three scenarios. Afterwards, a roadmap is constructed for the implementation of hydrogen in railways towards 2050.

5.1. Scenario I – 2030

The scenario covers 4 hydrogen trains in the Northern Netherlands over diesel-fueled lines. For $p = 1$, the simulation locates an HRS at Groningen. The results show that an HRS in Groningen alone captures approximately 25% additional flow compared to Leeuwarden, while distribution costs are half of that compared to Leeuwarden (see Appendix 6C). For an HRS in Groningen, 195 modules are needed per year, which is 97,500 kg hydrogen. Using a cost of $4/kg of hydrogen for 2030, the total costs amount to $390,000. A daily capacity of 500 kg or 1 module per day seems sufficient. The total building costs for an HRS with a daily capacity of 500 kg are approximately 2 million euros. The costs for 4 hydrogen trains amount to 5.2 million euros.

For the simulation with $p = 2$, both HRSs were able to refuel 100% of the flow. In total, a flow of 492,457 km was captured. Groningen captured 79.08% of the flow and Leeuwarden 20.92%. The HRS in Groningen refueled 8368 trips and the HRS in Leeuwarden refueled 2887 trips. The total hydrogen costs amount to $494,000. However, the results show a very low utilization of 2.85% on average for both HRSs. Figure 4 shows the results of scenario I. The figure covers the captured flow and the distribution cost per unit of flow. The figure shows that an HRS at both Groningen and Leeuwarden results in the highest captured flow. An HRS at Groningen is located the closest to the electrolysis facility in Delfzijl, resulting in the lowest distribution cost per unit of flow.

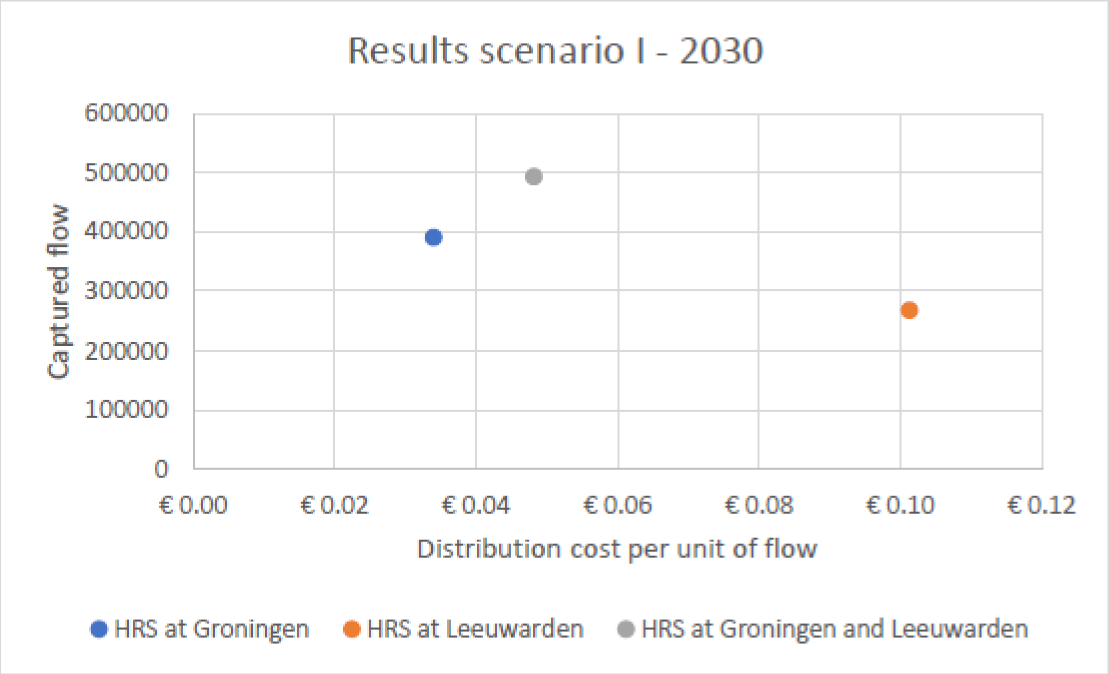


Figure 4: Results for scenario I.

Figure 5 shows the effect of decreased hydrogen consumption rate (2) and an increase in range (3) compared to the base scenario (1). It shows that an increase in achievable range has little effect on the amount of hydrogen needed, which is only a decrease of 0.11%. However, a decrease in hydrogen consumption rate from 0.25 kg/km to 0.225 kg/km results in a decrease of 10% in the amount of hydrogen needed.

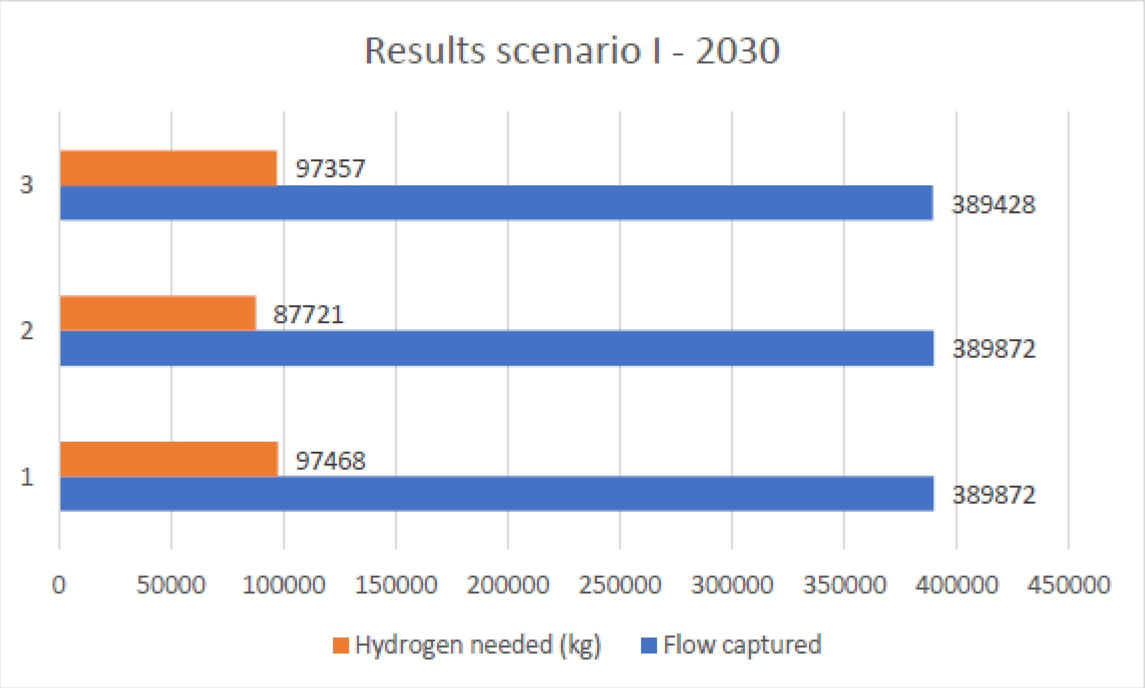


Figure 5: Hydrogen needed and flow captured for 2030.

5.2. Scenario II – 2040

The scenario covers 69 hydrogen trains in the Northern Netherlands. For $p = 1$, the simulation locates an HRS at Groningen. The results show that an HRS in Groningen alone captures 79.08% of the flow. 3023 modules are needed per year, which is 1,511,500 kg hydrogen. Using a cost of $3/kg of hydrogen for 2040, the total costs amount to $4,534,500 (see Appendix 6D). The costs for 69 hydrogen trains amount to 89.7 million euros.

For the simulation with $p = 2$, both HRSs were able to refuel 100% of the flow. 3023 modules are needed at the HRS in Groningen per year and 800 modules at the HRS in Leeuwarden per year. This corresponds to a daily capacity of 9 modules at Groningen and 2 modules at Leeuwarden. The total building costs for both HRSs are approximately 19 million euros. Using a cost of $3/kg of hydrogen for 2040, the total hydrogen costs amount to $5,734,500.

Figure 6 shows the results of scenario II. The figure covers the captured flow and the distribution cost per unit of flow. The figure shows that an HRS at both Groningen and Leeuwarden results in the highest captured flow. An HRS at Groningen is located the closest to the electrolysis facility in Delfzijl, thus resulting in the lowest distribution cost per unit of flow.

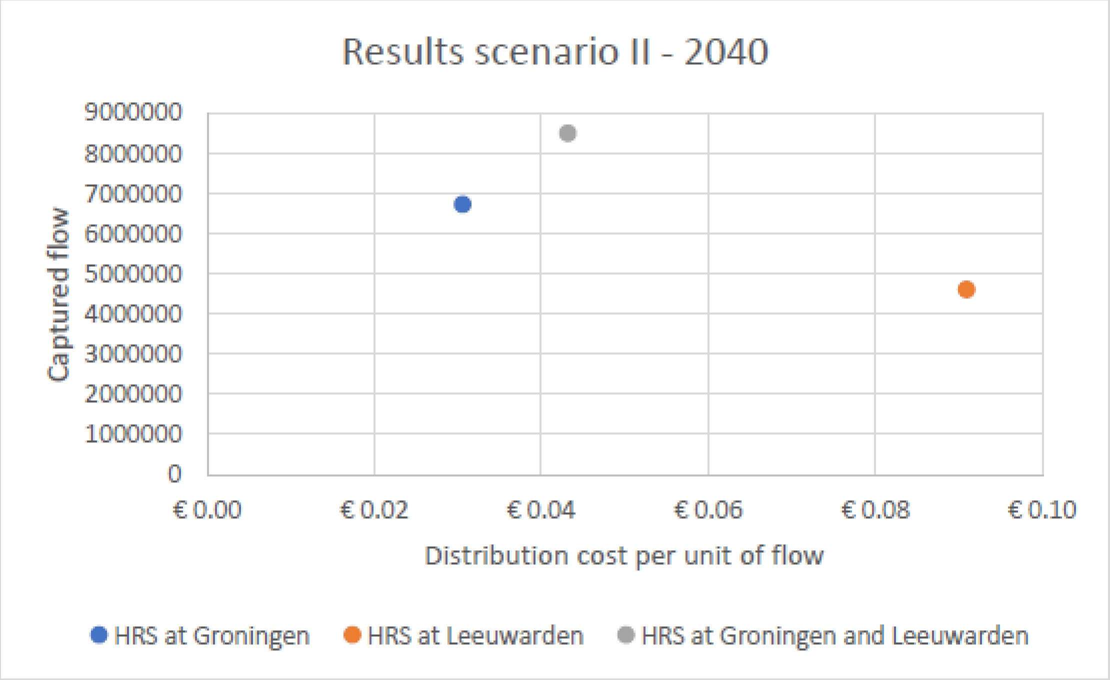


Figure 6: Results for scenario II

Figure 7 shows the effect of decreased hydrogen consumption rate (2) and an increase in range (3) compared to the base scenario (1). It shows that an increase in achievable range has little effect on the amount of hydrogen needed, which is only a decrease of 0.06%. However, a decrease in hydrogen consumption rate from 0.225 kg/km to 0.2 kg/km results in a decrease of 11.11% in the amount of hydrogen needed.

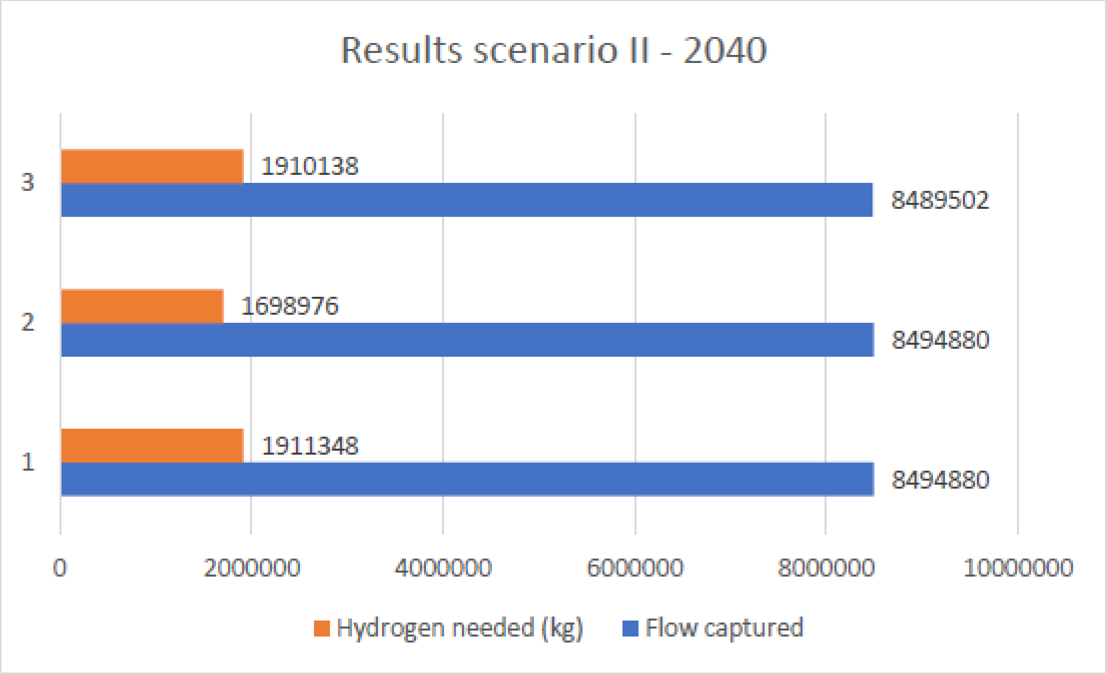


Figure 7: Hydrogen needed and flow captured for 2040

5.3. Scenario III – 2050

The scenario covers 69 hydrogen trains in the Northern Netherlands. For $p = 1$, the simulation locates an HRS at Groningen. The results show that an HRS in Groningen alone captures 79.08% of the flow. 2686 modules are needed per year, which is 1,343,000 kg hydrogen. Using a cost of \$2/kg of hydrogen for 2050, the total costs amount to \$2,686,000. The costs for 69 hydrogen trains amount to 89.7 million euros.

For the simulation with p = 2, both HRSs were able to refuel 100% of the flow. 2686 modules are needed at the HRS in Groningen per year and 711 modules at the HRS in Leeuwarden per year. This corresponds to a daily capacity of 8 modules at Groningen and 2 modules at Leeuwarden. Using a cost of \$2/kg of hydrogen for 2050, the total hydrogen costs amount to \$3,397,000. Figure 8 shows the results of scenario III. The figure covers the captured flow and the distribution cost per unit of flow. The figure shows that an HRS at both Groningen and Leeuwarden have the highest captured flow. An HRS at Groningen is located the closest to the electrolysis facility in Delfzijl, thus resulting in the lowest distribution cost per unit of flow.

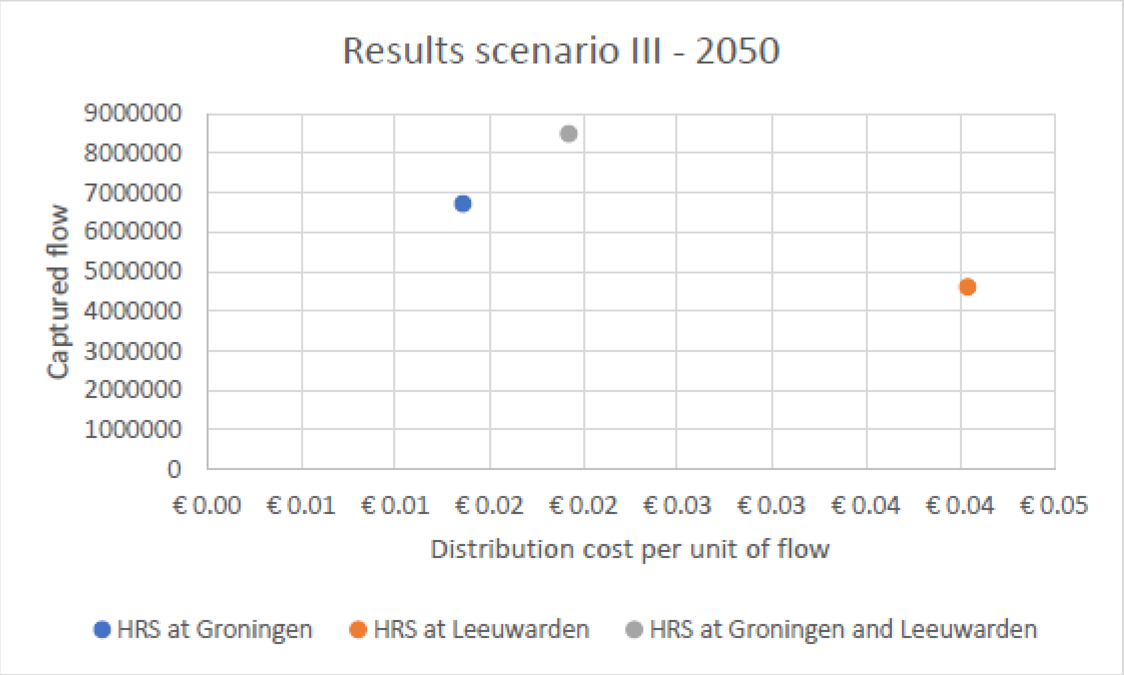


Figure 8: Results for scenario III

Figure 9 shows the effect of decreased hydrogen consumption rate (2) and an increase in range (3) compared to the base scenario (1). It shows that an increase in achievable range has little effect on the amount of hydrogen needed, which is only a decrease of 0.06%. However, a decrease in hydrogen consumption rate from 0.2 kg/km to 0.175 kg/km results in a decrease of 12.5% in the amount of hydrogen needed.

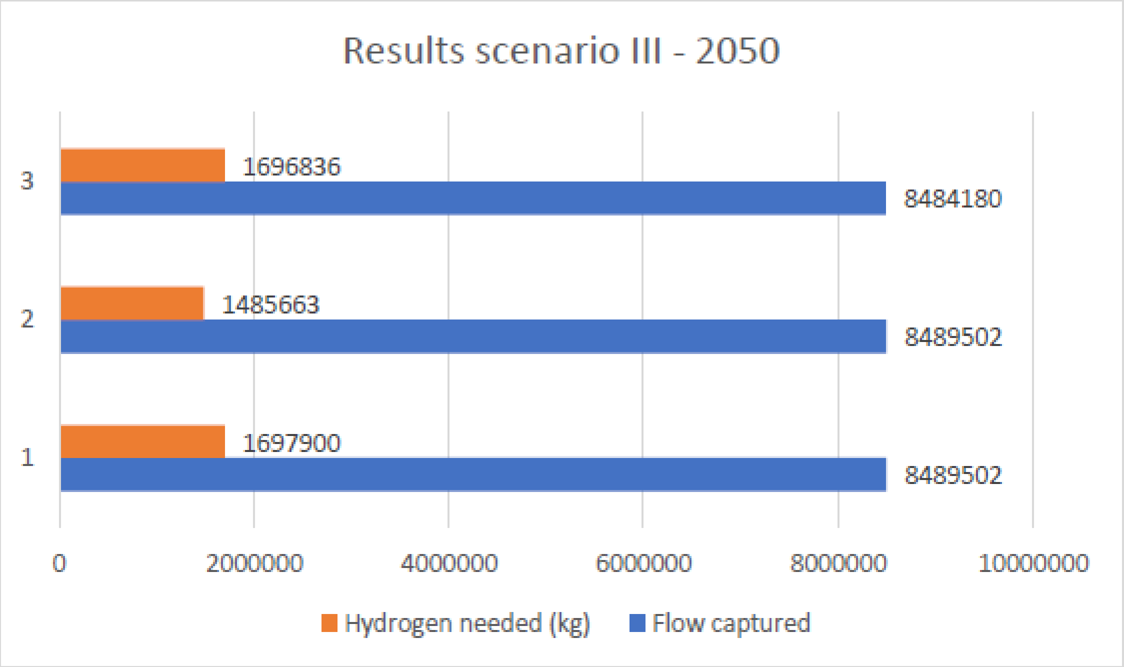


Figure 9: Hydrogen needed and flow captured for 2050

Table 3 shows the percentage of the total flow captured for possible combinations of refueling stations. The last column shows the relative difference for the captured flow of an HRS when an additional HRS is added. An additional HRS in Leeuwarden captures 33.29% less flow if an HRS is already at Groningen. This 33.29% of the flow is covered by both stations and allocated to Groningen as the distribution costs are less than the distribution costs to Leeuwarden. Therefore, improving cost-efficiency of the hydrogen network.

Table 3: Effect of an additional HRS to flow captured

Number of HRSs (p)	HRS location	Percentage of total flow captured	Difference relative to the capturable flow
1	Groningen	79.08%	-
1	Leeuwarden	54.21%	-
2	Groningen	79.08%	0%
2	Leeuwarden	20.92%	-33.29%

For example, using the total flow captured of 8,494,880, km, distributing 33.29% of the flow to Leeuwarden instead of Groningen accounts to 2,827,946 flow km or 1,414 modules of hydrogen, using a hydrogen consumption rate of 0.25 kg/km. Distribution costs for a module to Groningen are €68, while those to Leeuwarden are €202 for distribution by truck (based on a round trip, see appendix 6B). Therefore, resulting in cost savings of €189,476 per year. The use of pipelines would cut the total distribution costs in half (see Appendix 6E).

5.4. Roadmap

Looking at the results, the most cost-efficient investment decision would be to build one HRS in Groningen with a daily capacity of 500 kg per day for 2030. By 2040, the capacity of the HRS in Groningen should be upgraded to 4,500 kg per day (9 modules), and a new HRS should be built in Leeuwarden with a daily capacity of 1,000 kg, or 2 modules. By 2050, the capacity of the HRS at Groningen could be decreased to 4,000 kg per day as developments in fuel cell efficiency imply less hydrogen for refueling. The capacity of an HRS at Leeuwarden should not be changed (see figure 10). However, multiple developments are needed to reach these levels of hydrogen demand for railways in the future.

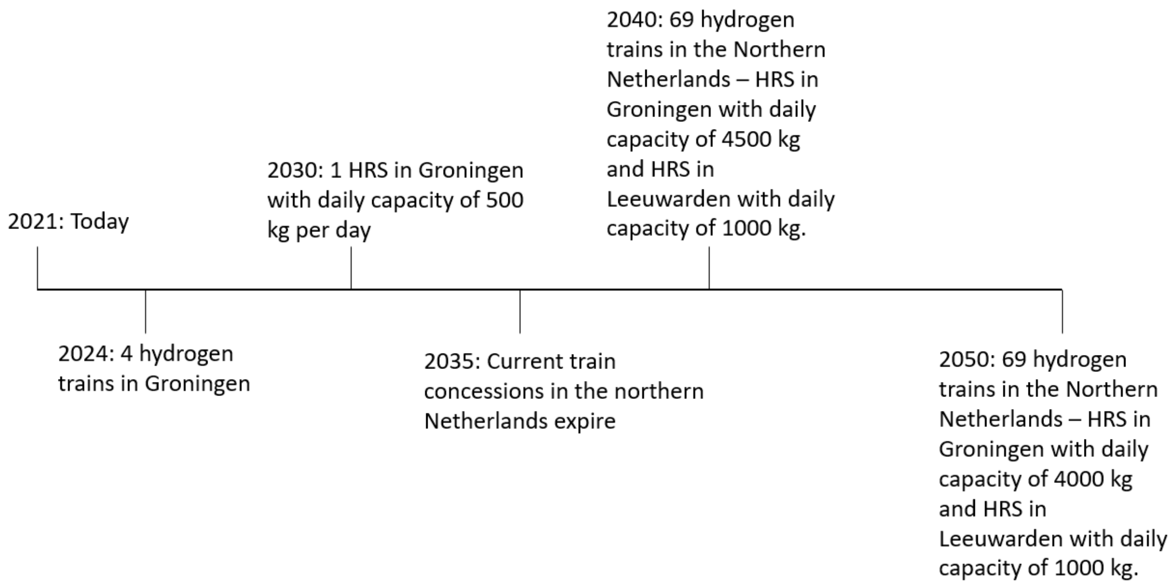


Figure 10: Roadmap towards 2050

Even more, it is unlikely that the actual capacity of an HRS will be downscaled in the future. Regulations should allow refueling of other modalities at HRSs for trains to accelerate economies of scale. This makes it more attractive for the government to make additional subsidies available as well. Besides, hydrogen should be distinguished from natural gas and fossil fuels. Current regulations are unreasonably high, which hinder adoption of hydrogen. Examples of barriers entail safety distances, storage amount, storage pressure, and transport guidelines as stated in PGS 35 and ADR. Less strict legislations stimulate developments and help to bring down the costs of a hydrogen infrastructure as well as the price per kg.

The investment costs are approximately 19 million euros for both HRSs, using capacities of 4,500 and 1,000 kg per day. In addition, the purchase of 69 hydrogen trains will cost about 89.7 million euros. The total investment costs amount to 108.7 million euros, which is way below the investment budget needed for full electrification of all unelectrified lines in the Northern Netherlands, which was calculated to be 593 million euros. The difference of 484.3 million euros is significant and can be used to offset the higher costs of hydrogen as a fuel. Using total hydrogen- and distribution costs of 6 million euros per year, which is in line with the scenario for 2040, the estimated savings can be used to finance 80 years of hydrogen use (484.3 / 6). The electricity costs for catenary electric trains are not included in this calculation, which would only make the difference greater.

The distribution costs could be reduced by building additional electrolysers close to HRSs and connecting electrolysers with an HRS through pipelines. This would ensure a reliable supply of hydrogen without strict capacity restrictions. While this is unlikely for 2030 due to low demand, regulations that allow hydrogen pressure of 700 bar for HDVs might be available by 2030. This could decrease distribution costs for transport by truck, as more hydrogen can be stored in the trailer. For 2040 and 2050, the connection of an HRS with the pipeline network would be beneficial due to the higher and dense demand of hydrogen at specific HRSs.

6. DISCUSSION

The results of the study are discussed in this section. The first scenario covers 4 hydrogen trains replacing all diesel-fueled trains in the Northern Netherlands for 2030. As a result, a low flow for hydrogen trains and a very low HRS utilization (< 5%) were shown. The simulation shows that an HRS at Groningen can capture 79.08% of the total flow, and can serve 100% of the flow related to Groningen. In addition, the simulation shows that an HRS in Groningen with a daily capacity of 500 kg is sufficient to cover the flow. Therefore, it would be wise to only build one HRS, which should be in Groningen. This saves approximately 10 million euros for an HRS in Leeuwarden. In addition, if the capacity of an HRS at Groningen would be set at 500 kg per day instead of 8,000 kg, this would save an additional 23 million euros. The total building costs would amount to 2 million euros.

The second and third scenarios assume all diesel-fueled trains are to be replaced by hydrogen trains, which is a possibility after the start of the new concession by 2035. These scenarios mainly cover developments in hydrogen price, distribution method, hydrogen consumption rate, and train range as shown in Table 2. The results showed that an increased fuel cell efficiency has the greatest impact on the amount of hydrogen needed, while an increased train range makes little impact. Based on this, hydrogen train manufacturing companies should prioritize improving fuel cell efficiency. However, it should be noted that an increase in train range requires trains to refuel less often. This means, fewer refueling moments need to be planned and fewer trains are needed to take over a train during refueling. This could result in lower investment costs as a hydrogen train costs around 1.3 million euros, as indicated by an interviewee. This is important to take into consideration for the total cost of ownership. Adjustments in regulations are needed to allow hydrogen storage pressure of 700 bar for trains, which could increase the range.

Figure 11 shows the amount of hydrogen needed, flow captured, and capacity of an HRS for the three scenarios. The scenarios cover an HRS in Groningen for 2030 and an HRS at both Groningen and Leeuwarden for 2040 and 2050. The parameter values for case (2) are used. It shows that the capacity exceeds the amount of flow captured for each scenario, meaning that all trains can be refueled. Capacity is measured as the amount of flow that can be refueled as explained in section 4. The building of the HRS in Leeuwarden results in additional capacity for 2040 and 2050. Furthermore, the replacement of all diesel-fueled trains by hydrogen trains for 2040 increases the captured flow and the amount of hydrogen needed. For 2050, the capacity increases as a lower hydrogen consumption rate implies an HRS being able to capture more flow. However, the captured flow stabilizes as no additional trains are used. The amount of hydrogen needed decreases as developments in hydrogen consumption rate and train range require less hydrogen for refueling.

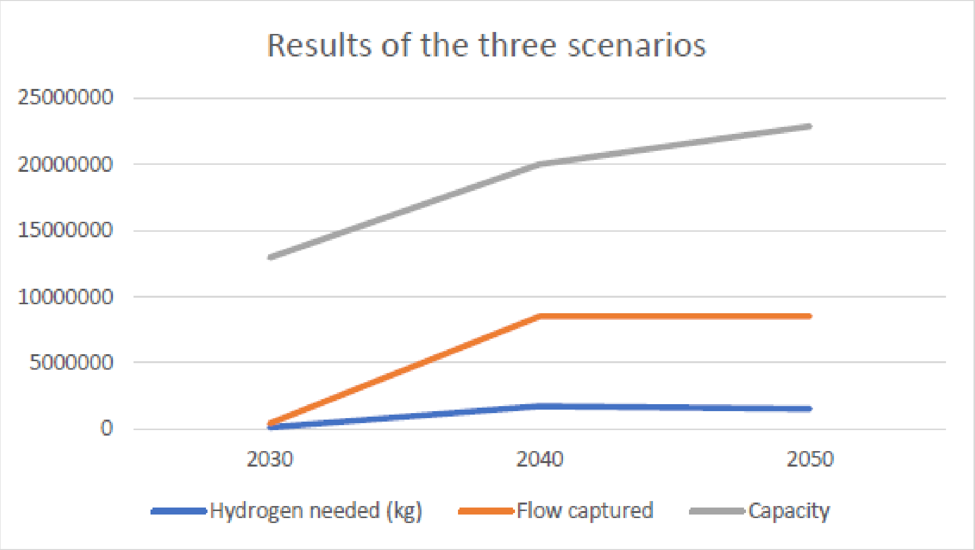


Figure 11: Overview of results

As illustrated in Figure 11, the capacities proved to be set too high. This is also reflected in the utilization of HRSs, which are less than 52% for the chosen combination of HRSs as shown in Appendices 4, 5, and 6. The difference can be explained by the fact that all flow is used from peak hours in the report from the provider company, while this study used actual flow data. In addition, the company stated that the capacities used in their report have a very large capacity compared to current practice. The overcapacity could be used for refueling of other modalities, dependent on adaptations in current regulations.

Altogether, the results are not ground breaking. Since HRSs could only be placed at marshalling yards, the potential HRS locations are heavily limited and strictly location-bound. In this study, this resulted in only two possible HRS locations. HRSs in the network need to cover every O-D pair as trains have predetermined routes and cannot run out of fuel. Even more, only one company is used as the provider of hydrogen, resulting in the lowest distribution costs for an HRS in Groningen. However, hydrogen will likely be distributed by multiple different suppliers in the future.

More weight has been given to the distance from an electrolysis facility to a potential HRS, than to the capacity of a potential HRS. Therefore, if a flow is captured by both the origin and destination station, the flow is dedicated to the HRS with the shortest distance towards the electrolyser facility. This constraint is justified as the capacity of a station is considered not to be a major barrier for the future. Namely, HRSs should be located at marshalling yards, which are outlying areas where more hydrogen is allowed to be placed. Furthermore, regulations are expected to develop in favour of storage quantities, which should allow more hydrogen to be stored at an HRS. On top of that, connecting the HRS with the pipeline network in the future would assure a stable supply of hydrogen. Hence, entities would do well to add more weight to the distribution costs than to capacity constraints. This constraint improves cost-efficiency due to lower distribution costs as well as the development of economies of scale at an HRS.

Managerial Implications

Managers and people involved in the development of hydrogen applications in railway transport can use several insights from this study. First, refueling logistics showed to be comparable with diesel-fueled trains. Second, it is important to carefully plan and coordinate investments among multiple levels of governance, as many uncertainties exist. If the hydrogen network is developed too quickly, it can lead to a waste of money. Third, the provinces of Friesland and Groningen have commissioned research into the building of two HRSs, however, the results of the simulation showed that one HRS in Groningen is more cost-efficient for 2030 due to low hydrogen demand. This finding is consistent with the second statement that entities should not invest too much in the network while the future is unclear. In addition, the capacities that are currently mentioned for HRSs in Leeuwarden and Groningen can be reduced if regulations are not adjusted, as HRSs for railways are not allowed for other modalities.

7. CONCLUSION

This study investigated potential hydrogen refueling station locations for railway transport, as diesel-fueled trains will be replaced to reduce CO2 emissions. No research had yet been done on the development of a hydrogen infrastructure for railways, therefore a flow-interception location model is used to determine optimal HRS locations for this application in the Northern Netherlands. The application of green hydrogen in railway transport is a promising alternative for expensive electrification, but the future is unclear. The technology is feasible, but the high costs and lacking infrastructure hinder adoption as of today. Prices are expected to drop in the future, but it is difficult to predict future hydrogen demand in railways as many aspects for the application of hydrogen need to be developed further. Factors influencing future hydrogen demand in railways concern the availability of subsidies, government policies, regulations, and technological developments. Little subsidies are available for HRSs for railways as these can only be used by trains, which hinders adoption. Government policies concern, among other things, which applications hydrogen should be used for and where it should be produced. Current policy states that hydrogen should mainly be used for applications where no alternatives, such as electrification, are present. Thus, prioritizing the use of hydrogen for use cases such as steel production, chemical production, and as a fuel for transportation modes that are difficult to electrify. This could mean that the use of hydrogen in trains could be limited for the near future. Regulations concern the unreasonably high legislations that apply to hydrogen, as it is classified in the same group as natural gas and fossil fuels. As a result, entities involved with hydrogen need a permit and comply with PGS 35 that states location-specific rules regarding storage amount and distances. Also, hydrogen is included in Annex A of ADR, which states strict transport guidelines. Lastly, technological developments relate to fuel cell efficiency, achievable range, distribution methods, and hydrogen price. Developments in these areas help to reduce the total cost of ownership of hydrogen trains and the infrastructure. The scenarios showed that developments in fuel cell efficiency have a greater effect on the amount of hydrogen needed compared to developments in achievable range.

The results of this study showed that current calculations for HRSs in Groningen and Leeuwarden have overcapacity. This study showed that an HRS in Groningen with a daily capacity of 500 kg is sufficient to serve demand in 2030. By 2040, an HRS with a daily capacity of 4,500 kg in Groningen and 1,000 kg in Leeuwarden are needed. By 2050, the HRS at Groningen needs a daily capacity of 4,000 kg and Leeuwarden 1,000 kg. An HRS for trains is not allowed to be used by other modalities as of today. The connection of HRSs with the pipeline network could bring distribution costs down and assure permanent supply of hydrogen in the future.

Developments in the future will decide whether the railway sector will opt for hydrogen or another alternative. Competitive alternatives are full electrification and the battery train. Therefore, it is recommended to be reluctant with high investments as of today. An increasing carbon price could accelerate the replacement of diesel-fueled trains. Besides, more stimulating policies and European standardization are needed for broad adoption of hydrogen in railways. The developed model can be used to locate hydrogen refueling stations when hydrogen trains will be adopted in the future.

Limitations

Some limitations must be taken into account within this study. First, the distance from origin to destination received in the data files was not reliable. Besides, these distances were not available online for railway transport. Therefore, the distance from origin to destination was attained through Google Maps. The travel path is verified by checking the NS Reisplanner. As a result, the travel distance is not identical to the actual distance that a train travels, but the difference is not significant for purposes of this study.

Also, this study used percentages of the total flow, resulting in calculations with non-integer trains. Besides, averages of hydrogen demand are used. So the results do not cope with big fluctuations in demand at an HRS. However, this is not a problem for purposes of this study as the application of hydrogen in railways is still in the development stage.

Future research

Future research could use the developed model and apply flow data from other countries. An interesting application could be the railway network of the United States, as the USA has mostly diesel-fueled lines and long distances in between origin and destination stations. Also, the application of hydrogen for trains with a hybrid bi-modal propulsion system in regions with both catenaries and non-electrified lines could be interesting to investigate. For example, for the four provinces in the Netherlands: Groningen, Friesland, Overijssel, and Gelderland.

The reformulation of the flow resulted in a more precise calculation for the amount of hydrogen needed. Therefore, the model could be used to determine optimal locations for refueling stations for us in other modalities or other fuels.

Furthermore, future research could consider potential HRS location decisions based on a railway company's point of view. This study determined optimal HRS locations from an infrastructural point of view. Additionally, an extensive total cost of ownership analysis between hydrogen and electric and diesel-fueled trains is recommended when more information is available. This could give deeper insights into the business case of hydrogen from a company's point of view.

Lastly, future studies could include the effect of weather conditions, as mentioned by Kumar & Bierlaire (2015). This would result in more precise calculations of hydrogen demand and different values for hydrogen consumption and achievable range per travel path. For example, coastal routes could imply higher hydrogen consumption compared to inland routes due to differences in wind speed.

Literature

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Appendix 6A – Detailed formulas for the objective function

$$Max\ Z \qquad \sum_{q\in Q} f_q * y_q$$

$$f_q \qquad \sum_{k\in K}\sum_{i\in I}\sum_{j\in J}(D_{ki} + D_{kj})$$

$$DD_{ki} \qquad \sum_{q\in Q}\sum_{i\in I}\sum_{k\in K}((freq_q * d_q + \frac{freq_q}{\frac{range}{d_q}} * d_{HRSki}) * x_k)$$

$$DD_{kj} \qquad \sum_{q\in Q}\sum_{j\in J}\sum_{k\in K}((freq_q * d_q + \frac{freq_q}{\frac{range}{d_q}} * d_{HRSkj}) * x_k)$$

$$D_{ki} \qquad \sum_{q\in Q}\sum_{i\in I}\sum_{j\in J}\sum_{k\in K}((freq_q * d_q + \frac{freq_q}{\frac{range}{d_q}} * d_{HRSki}) * x_k) - DD_{kj} \quad \forall\, CD_{ki} > CD_{kj}$$

$$D_{kj} \qquad \sum_{q\in Q}\sum_{i\in I}\sum_{j\in J}\sum_{k\in K}((freq_q * d_q + \frac{freq_q}{\frac{range}{d_q}} * d_{HRSkj}) * x_k) - DD_{ki} \quad \forall\, CD_{kj} > CD_{ki}$$

$$CD_{kj} \qquad d_{HRSke} * DT_{km}$$

$$CD_{ki} \qquad d_{HRSke} * DT_{km}$$

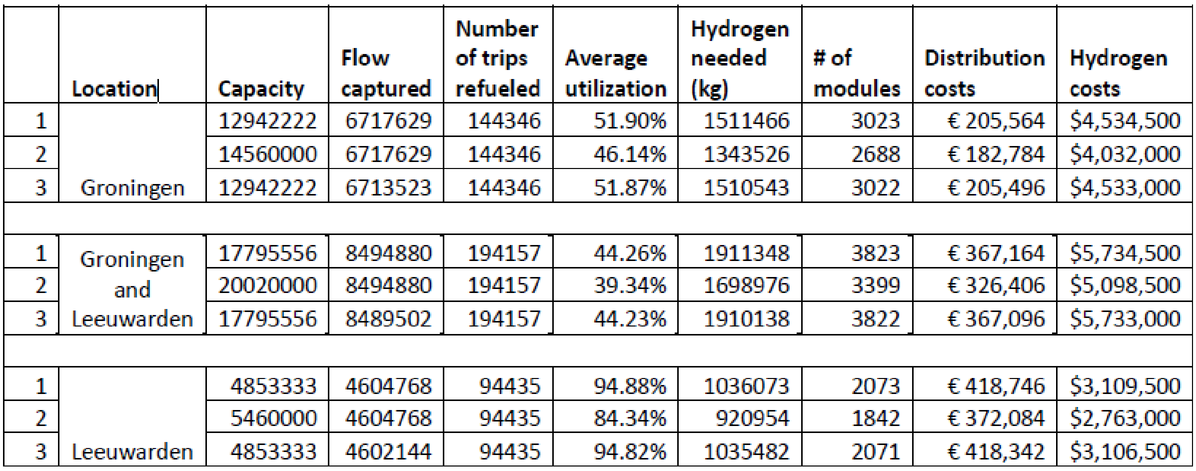
Appendix 6B – Travel distances

Destination \ HRS	Groningen	Leeuwarden
Electrolyser Delfzijl	34	101
Veendam	36	
Winschoten	40	
Roodeschool	35	
Delfzijl	32	
Weener	63	
Harlingen Haven		28
Sneek		27
Stavoren		53
Leeuwarden	63	-
Groningen	-	63

Appendix 6C – Results Scenario I

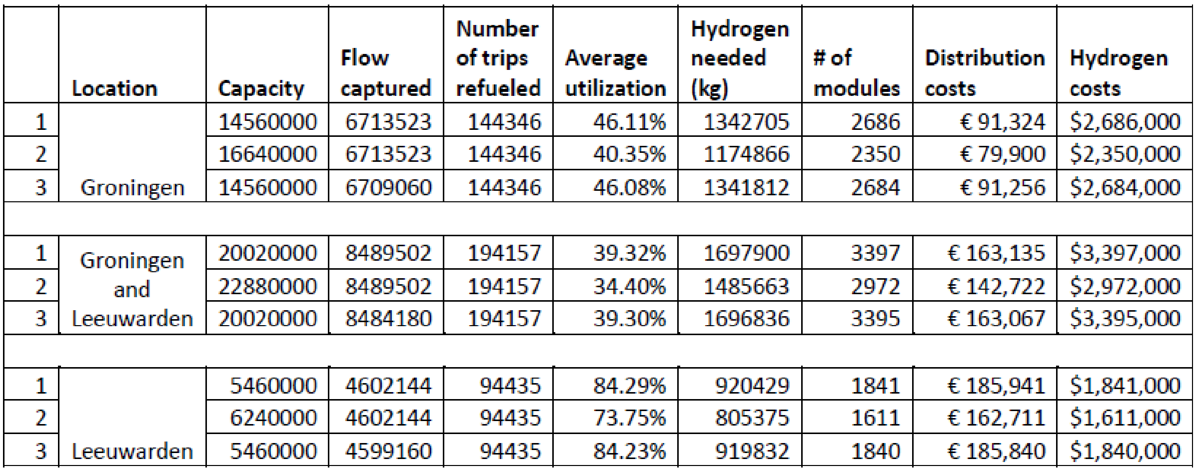
	Location	Capacity	Flow captured	Number of trips refueled	Average utilization	Hydrogen needed (kg)	# of modules	Distribution costs	Hydrogen costs
1	Groningen	11648000	389872	8368	3.35%	97468	195	€ 13,260	$ 390,000
2		12942222	389872	8368	3.01%	87721	176	€ 11,968	$ 352,000
3		11648000	389428	8368	3.34%	97357	195	€ 13,260	$ 390,000
1	Groningen and Leeuwarden	16016000	493006	11255	2.85%	123252	247	€ 23,764	$ 494,000
2		17795556	493006	11255	2.57%	110926	223	€ 21,462	$ 446,000
3		16016000	492457	11255	2.85%	123114	247	€ 23,764	$ 494,000
1	Leeuwarden	4368000	267257	5474	6.12%	66814	134	€ 27,068	$ 268,000
2		4853333	267257	5474	5.51%	60133	121	€ 24,442	$ 242,000
3		4368000	266943	5474	6.11%	66736	134	€ 27,068	$ 268,000

Appendix 6D – Results Scenario II



	Location	Capacity	Flow captured	Number of trips refueled	Average utilization	Hydrogen needed (kg)	# of modules	Distribution costs	Hydrogen costs
1	Groningen	12942222	6717629	144346	51.90%	1511466	3023	€ 205,564	$4,534,500
2		14560000	6717629	144346	46.14%	1343526	2688	€ 182,784	$4,032,000
3		12942222	6713523	144346	51.87%	1510543	3022	€ 205,496	$4,533,000
1	Groningen and Leeuwarden	17795556	8494880	194157	44.26%	1911348	3823	€ 367,164	$5,734,500
2		20020000	8494880	194157	39.34%	1698976	3399	€ 326,406	$5,098,500
3		17795556	8489502	194157	44.23%	1910138	3822	€ 367,096	$5,733,000
1	Leeuwarden	4853333	4604768	94435	94.88%	1036073	2073	€ 418,746	$3,109,500
2		5460000	4604768	94435	84.34%	920954	1842	€ 372,084	$2,763,000
3		4853333	4602144	94435	94.82%	1035482	2071	€ 418,342	$3,106,500

Appendix 6E – Results Scenario III



	Location	Capacity	Flow captured	Number of trips refueled	Average utilization	Hydrogen needed (kg)	# of modules	Distribution costs	Hydrogen costs
1	Groningen	14560000	6713523	144346	46.11%	1342705	2686	€ 91,324	$2,686,000
2		16640000	6713523	144346	40.35%	1174866	2350	€ 79,900	$2,350,000
3		14560000	6709060	144346	46.08%	1341812	2684	€ 91,256	$2,684,000
1	Groningen and Leeuwarden	20020000	8489502	194157	39.32%	1697900	3397	€ 163,135	$3,397,000
2		22880000	8489502	194157	34.40%	1485663	2972	€ 142,722	$2,972,000
3		20020000	8484180	194157	39.30%	1696836	3395	€ 163,067	$3,395,000
1	Leeuwarden	5460000	4602144	94435	84.29%	920429	1841	€ 185,941	$1,841,000
2		6240000	4602144	94435	73.75%	805375	1611	€ 162,711	$1,611,000
3		5460000	4599160	94435	84.23%	919832	1840	€ 185,840	$1,840,000