Structuring the Hydrogen Refueling Station Network to accommodate Fuel Cell Electric Trucks: A study in the Northern Netherlands.

Hidde Scholten, Evrim Ursavas, Nicky van Foreest

1. INTRODUCTION

Road freight transportation accounted for 2.3 Gt of CO2 emissions in 2016 (IEA, 2019), which translates to approximately 15% of total CO2 emissions (Our World in Data, 2020). Whereas most sectors have already been able to reduce emissions gradually over the course of the past decades, the transportation sector has notably seen an increase of 4.4% from 1990 to 2014 (EEA, 2016). Structurally reducing the CO2 emissions in this sector will thus mark a significant contribution in addressing climate change. This calls for a fundamental shift towards low- and zero-emission alternatives for vehicle propulsion. Not only the direct emission from vehicles but the emissions from energy generation to end-use -also known as well-to-wheel (WTW) emissions- should drastically be reduced. Green hydrogen, produced from renewable energy sources (RES), is a potential candidate for fulfilling this role (Talebian et al., 2018). Propulsion of long-haul road freight with hydrogen in fuel cell electric trucks (FCET) could potentially contribute to the decarbonisation of the sector. Compared to battery electric trucks (BET), FCETs have several advantages. The combination of longer driving ranges and shorter refuelling times makes hydrogen a promising option for heavy-duty vehicle applications (Lee et al., 2018; Rose & Neumann, 2020).

One of the major barriers to the wide-scale adoption of fuel cell electric trucks (FCET) in the road freight sector is the lack of refuelling infrastructure and the lack of economic viability in terms of ownership costs (Liu et al., 2020), which results in a problem often defined as the “chicken and egg” problem (Ajanovic & Haas, 2018; Isaac & Saha, 2021; MirHassani & Ebrazi, 2013). That is, there exists a two-way relationship between refuelling infrastructure and demand for FCETs. Investments in hydrogen refuelling stations (HRS) will only be attractive when there are sufficient FCETs on the road that need hydrogen to complete their trips. Controversially, there is little incentive for companies to buy FCETs when there is no refuelling infrastructure in place (Apostolou & Xydis, 2019). In the alternative fuels infrastructure directive (AFID), a refuelling infrastructure for alternative fuel vehicles (AFV) in EU member states is specifically called for, and a guideline to national policy frameworks that support this development is presented (EC, 2014). It underlines the importance of a widespread refuelling infrastructure to stimulate the adoption of FCETs among transportation companies.

In that context, an important question is how many HRS facilities to build and where to locate them. A commonly used model to optimally determine HRS structures is the flow refuelling location model (FRLM). The FRLM optimally locates a number of refuelling locations along a network to maximize the total flow volume refueled (Kuby & Lim, 2005). There is a substantial number of papers in the literature that use the FRLM to develop HRS structures for passenger vehicles (Capar et al., 2013; Kuby & Lim, 2005; Lim & Kuby, 2010; MirHassani & Ebrazi, 2013; Rose & Neumann, 2020). Nonetheless, to the knowledge of the author, there is only one article written by Kluschke et al. (2020) that uses the FRLM to determine an HRS structure for FCETs. It is of high importance to separately investigate HRS requirements for each heavy-duty applications, because their routing behaviour, fuelling requirements, and driving ranges are completely different (Rose & Neumann, 2020). A useful contribution in the work of Kluschke et al. (2020) is the inclusion of capacity restrictions of HRS, which makes the model more realistic. Nonetheless, a major flaw by Kluschke et al. (2020) is that they only consider one point in time, which is 2050 and they assume that all heavy-duty trucks (HDT) are replaced by FCETs. Therefore, a more realistic approach is to gradually increase the share of FCETs in the market over time and observe the different HRS structure requirements for different scenarios. In addition, the costs associated with building an HRS have not yet been taken into consideration when locating HRS facilities for FCETs. These gaps in the literature are filled in by answering the following research question in the remainder of this study;

How to structure a Hydrogen Refuelling Station Network to accommodate Fuel Cell Electric Trucks? A study in the Northern Netherlands.

The first step is to perform an extensive literature review on green hydrogen, FCETs, and HRS infrastructures. Next, existing refuelling station location models are assessed, and the model used in this study is accordingly positioned amongst the relevant literature. After this, the main barriers that are currently preventing the FCET and HRS market to grow are identified, as these will be key in the evaluation of the results.

For the case study, an extensive qualitative research is performed by interviews and by gathering data from different firms and institutions involved in the transportation sector in the Northern Netherlands for HEAVENN. The goal is to develop an integrated green hydrogen economy, in which the end-use of green hydrogen in transportation is an important aspect. The chosen model from literature will be used to determine the costs, locations, and number of HRS facilities for FCETs under different scenarios, based on origin-destination (OD) flows of HDTs in the region.

Finally, the results of this analysis are used to reflect on the different scenarios by means of a thorough discussion with companies and linking the findings back to the literature and the identified barriers. The discussion of the results and the conclusion on how to overcome the barriers constitute an important practical contribution. The uncertainty among potential HRS investors that revolves around the costs, locations, and the number of HRS facilities needed is reduced. Moreover, the conclusions can be used as guidelines for policymakers to decide on budget allocations and regulatory frameworks. The findings have been summarized in a compact roadmap. From a theoretical point of view, this study contributes to existing literature by filling in the lack of research on HRS structures for FCETs. More specifically, a multi-period, multi-scenario and in-depth case study is conducted, thereby increasing the relevance to a real-world context. In addition, the costs of building an HRS for FCETs are integrated into the FRLM, which serves as a significant contribution to the work of Kluschke et al. (2020).

In the next section a structured theoretical background can be found. Next, the methodology of this study is thoroughly discussed. Then, the case study is introduced, and the model will be applied to the Northern Netherlands, after which an extensive discussion will be provided on the results. Finally, a concise conclusion will be presented, along with the limitations and future research suggestions.

2. THEORETICAL BACKGROUND

In this section, the theoretical background of this research is presented. First, the relevance of green hydrogen is explained. Secondly, up-to-date literature about FCETs will be assessed. Thirdly, relevant refueling station location models are explored, thereby providing the foundation for the methodology section of this research. By assessing and synthesizing these sources of literature, a justifiable gap is identified, and this study is positioned within these streams accordingly.

After this, the main barriers to large-scale adoption of hydrogen in heavy-duty transportation are identified. This section concludes with the main theoretical and practical contributions from this research.

2.1. Green Hydrogen

For a FCET to be ‘truly’ zero-emission, green hydrogen must be used and the WTW chain should be completely emission-free. Green hydrogen can be produced through electrolysis, which is a process in which water is split into hydrogen and oxygen by using electricity. This electricity should thus also come from renewable energy sources (RES) to be truly green (Apostolou & Xydis, 2019; Burkhardt et al., 2016; Çabukoglu et al., 2019; Talebian et al., 2018). An alternative to green hydrogen is blue hydrogen, which is hydrogen produced through Steam Methane Reforming (SMR) with carbon capture and storage (CCS). This technology is not zero-emission, but reducing the emissions in the production of hydrogen (Körner, 2015). However, this is not a sustainable solution, because of limited storage place for captured CO2, social acceptance issues, and a lack of required technological systems (International Energy Agency, 2020). In the short term, blue hydrogen is needed to accommodate and incentivize the uptake in demand for hydrogen, as major renewable energy plants and electrolysers are being built. As described in the Dutch Climate Agreement (2019), sufficient blue hydrogen must optimally contribute to the development of an integrated hydrogen system, however it cannot stand in the way of the growth of green hydrogen. The renewable energy grid should thus be optimised for green hydrogen to be abundantly produced and to provide meaningful and sustainable GHG reductions (Haugen et al., 2021; Miotti et al., 2017). Once green hydrogen is produced and sufficiently available, its end-use is clean and diverse, and can be used for manufacturing industries, residential heating but also road transportation (Körner, 2015). When used as a propulsion fuel for vehicles with fuel-cell technology, the only emission that is released is water from the tailpipe (Singh et al., 2015).

2.2. Fuel Cell Electric trucks

In decarbonizing the transportation sector, battery electric vehicles (BEV) are currently the prevalent and most popular alternative, especially in the light-duty vehicle sector. Whereas BEVs are more likely to be the dominant sustainable alternative for light-duty vehicles, heavy-duty road freight could benefit more from hydrogen as the sustainable solution (Moriarty & Honnery, 2019). Forrest et al. (2020) looked into the technical feasibility of FCETs compared to BETs. They made a distinction between different sizes of trucks and found that FCEV feasibility increases with the size of a truck - that is, long-haul trucks- as refueling times are much shorter and large BETs need heavy batteries which affect payload ratings. The advantage of FCETs over BETs also has to do with the fact that FCETs have no battery degradation problems, and they have the capability of long-term on-board storage of the hydrogen fuel without energy losses (Apostolou & Xydis, 2019). BET powertrains are in some cases able to supply the required energy for short daily trips, however for long-haul freight, the low energy density of batteries in BETs is a major disadvantage, as it negatively affects the driving range on one load (Talebian et al., 2018).

Only small trucks or vans that have urban delivery schedules with relatively short and pre-defined routes might benefit more from BETs than FCETs (Talebian et al., 2018). In the short-term, researchers expect the two technologies to emerge complementarily, as infrastructures are being developed which require heavy investments (Anandarajah et al., 2013; Morrison et al., 2018; Talebian et al., 2018). However, Anandarajah et al. (2013) argue that in the long-term -as hydrogen WTW costs gradually decline- a more competitive interaction between the technologies can be expected. Morrison et al. (2018) performed a Total Cost of Ownership (TCO) analysis and found that by 2030 the cost advantages of BETs over FCETs (even in light-duty vehicles) quickly diminish. They call for further research in the field of FCETs and HRS infrastructure, which motivates this study.

2.3. Hydrogen Refueling Stations

The process of delivering hydrogen to vehicles by an HRS can be split up into several stages. First, the hydrogen needs to be supplied to the HRS. Usually, hydrogen is produced off-site and is supplied in either gaseous or liquid form. Gaseous hydrogen (G.H2) can be delivered to an HRS either by a pipeline or a truck carrying tube trailers (Apostolou & Xydis, 2019). Off-site produced hydrogen might require on-site purification to comply with purity standards (PGS35, 2020). Liquid hydrogen (L.H2) is produced off-site, which is also delivered by trucks, and it must be stored at cryogenic temperatures below -252.87 °C. At the HRS it can be stored in large tanks, after which it has to be transformed into gas on-site (Apostolou & Xydis, 2019). The hydrogen can also be produced on-site through an electrolyser, however this method adds constraining capacity limits to the amount of hydrogen that can be dispensed, which is usually not more than 100kg H2 per day (Apostolou & Xydis, 2019). After the hydrogen has been delivered, it needs to be compressed, so that it can be stored in large quantities at the HRS without taking up much space at the HRS (Körner, 2015). In addition, high-pressure buffer storage must be in place to prevent having to compress a new ‘batch’ of hydrogen each time a FCET has refuelled at the station (Apostolou & Xydis, 2019). Finally, a cooling system is needed, to bring down temperatures as the hydrogen heats up during the refuelling process (Burkhardt et al., 2016). All these elements of an HRS come at a considerable cost, which will be discussed in the Section 4 of the case study.

2.4. Refueling Station Location Models

An HRS infrastructure able to support the promotion and application of hydrogen FCETs is currently not present, and this poses one of the biggest obstacles to the full-scale adoption of hydrogen in transportation (Lin et al., 2020). Determining this structure relates to the facility location problem (FLP). Three basic FLPs can be identified, namely the covering problem, p-median model, and p-center model (Lin et al., 2020). These models are all categorized as node-based problems, in which demand is aggregated in nodes (MirHassani & Ebrazi, 2013). The covering problem focuses on whether a demand node can be covered by a station node based on the distance between the nodes. The p-median model minimizes the aggregate distance to a demand node by assigning demand as a weight to distance. Finally, the p-center model aims to minimize the maximum weighted distance between a demand point and its assigned station node. Although these models are widely recognized and applicable in many situations, a more popular method in recent literature -and specifically for locating refueling stations- are flow-intercepting models. Hodgson (1990) first introduced the flow capturing location model (FCLM). In this model, demand is associated with a traffic flow between a set of origin-destination (OD) pairs. The objective function here seeks to maximize the captured flow accordingly. The main flaw of the FCLM was addressed by Kuby & Lim (2005), which is that the FCLM does not allow a vehicle to refuel more than once on a trip. Moreover, many authors have extended and contributed to the FRLM, which makes it more relevant and up to date. Even for relatively concentrated study areas with only one required fuel stop for each trip, the constraints from the FCLM and FRLM entail the same logic so the FRLM can be used for small areas as well (Upchurch et al., 2009).

Upchurch et al. (2009) first introduced the Capacitated FRLM (CFRLM). This was an important step in making the FRLM more relevant for real-world contexts. Capar & Kuby (2013) reformulated this work by using a set covering version of the FRLM (SC-AC-PC model), in which the objective is not to maximize the total refueled traffic flow, but to minimize the number of stations needed to cover a given demand share. This set-covering approach is specifically relevant to this study because it can assist in assessing HRS infrastructure requirements that come along with an expected percentage of FCET market penetration. For instance, the approach answers the number of HRS facilities needed if 10% of the HDT market is comprised of FCETs. Kluschke et al. (2020) extended the work of Capar & Kuby (2013), and they were the first to analyse a set-covering HRS infrastructure with node capacity restrictions for the HDT sector. The FRLM was applied to a case study in which the assessment of a widespread HRS infrastructure in Germany was presented.

In this study, the FRLM used by Kluschke et al. (2020) will be taken as a base model. This study will contribute to the existing literature by adapting the FRLM to account for cost considerations in locating HRS facilities for FCETs. In addition, multiple periods with different scenarios are run by the model that will serve the purpose of building towards an extensive roadmap, from which practical conclusions can be drawn. The complete model, its components, and adaptations to the model that fit the purpose of this research will be further elaborated on in the methodology section. Based on the analysis of current flow refueling location models, a visual representation of the position of this study amongst relevant literature, Table 1: Positioning amongst relevant literature is presented below.

TABLE 1: POSITIONING AMONGST RELEVANT LITERATURE

	Model used	FCEV/FCET	Set Covering	Objective flow refuelling percentage	Capacitated	Real-word case study	Multi-Period	Multi-Scenario	Regulatory context	Cost Considerations
(Kuby & Lim, 2005)	FRLM	FCEV				✓				
(Upchurch et al., 2009)	CFRLM	FCEV			✓	✓				
(Lim & Kuby, 2010)	FRLM	FCEV								
(Capar et al., 2013)	(SC-AC-PC) FRLM	FCEV	✓	✓						
(Kluschke et al., 2020)	(NC) FRLM	FCET	✓		✓	✓			✓	
Scholten (2021)	**(SC-NC) FRLM**	**FCET**	✓	✓	✓	✓	✓	✓	✓	✓

2.5. Barriers

The next step is to identify the barriers that are currently constraining the large-scale adoption of hydrogen in heavy-duty transportation. The barriers have been split up into economic, regulatory, technical and safety barriers.

2.5.1. Economic Barriers

One of the main economic burdens to the adoption of hydrogen as a transportation fuel is that fossil fuels have continued to be available in the quantities needed, therefore being affordable to the majority of people (Moriarty & Honnery, 2019). From an economical perspective, there is thus little incentive to switch to expensive FCETs. The TCO of a FCET is currently significantly higher than the TCO of a diesel or BET alternative (Hall & Lutsey, 2019).

The other end of the story is the high price of constructing an HRS. The costs of building an HRS are significantly higher than building a conventional gas station. A fuel cell partnership in California estimates the price of an HRS for passenger vehicles with gaseous H2 delivery and a capacity of 180 kilograms to be around 2 million Dollars, or approximately 1,680 million Euros (H2 Station Maps, 2020). The costs of a compressor that is needed to pressurise hydrogen to the required level (700 bar for passenger vehicles, and 350 bar for heavy-duty vehicles) is by far the largest cost component (Parks et al., 2014). Parks et al. (2014) performed an extensive investigation into the costs of building an HRS facility. The Capital Expenditure (Capex) of a compressor was estimated to be between 1 and 1.5 million dollars (roughly 800,000 - 1M euros). Moreover, the storage costs of hydrogen at an HRS facility would also make up a large portion of the total costs. Compressed hydrogen needs to be temporarily stored with high pressure to account for fluctuation in demand and therefore act as a buffer. These costs range between 150,000 and 250,000 dollars (roughly 125,000-200,000 euros). Conclusively, they found the total costs of building an HRS facility ranges between 2M and 2.5M euros. To put this in perspective, the costs of building a conventional gas station are roughly between 100,000 and 300,000 euros.

Another main economic barrier is the high supply costs of green hydrogen. The Dutch Environmental Assessment Agency (PBL) conducted a study in 2020 to calculate the production costs including storage and transportation of blue and green hydrogen in 2030. They use a low, middle, and high scenario. The results showed a green hydrogen price ranging from €2,40 to €5,27 per kg in 2030 (PBL, 2020). Nevertheless, they acknowledge that this is based on optimistic assumptions, in which for instance electrolyser costs should halve in 10 years. They argue that in the short term, blue hydrogen with CCS storage is cheaper, however the price difference will diminish moving towards

2040. To speed up the cost reductions of green hydrogen in the Netherlands, large wind parks are needed to produce enough RES to produce the hydrogen (New Energy Coalition, 2020).

2.5.2. Regulatory Barriers

HyLAW has created an extensive database with reports on legal and administrative processes (LAPs) around hydrogen in Europe (HyLaw, 2021). In the report specifically devoted to LAPs in the Netherlands, two LAP barriers were identified (van der Meer et al., 2018). Fuel origin and certification is the first, in which they argue that the absence of a common definition (Guarantee of Origin, GoO) for green hydrogen hinders the development of a widespread hydrogen market. They add that the Renewable Energy Directive II (RED II) does not provide sufficient room to label all renewable hydrogen 'green'. The RED II is a legally binding directive first established in 2009, and in 2018 it has been revised, setting the binding renewable energy target for all member states to 32% in 2030 (*Renewable Energy Directive | Energy*, 2014). RED II states that green hydrogen can only be supplied through newly developed RES stations, and not from currently existing renewable power sources. However, because green hydrogen production currently has no significant economies of scale to be widely economically attractive, the RED II requirement hinders the process of scaling up significantly. Therefore, the New Energy Coalition (2020) also calls for immediate and temporary exemption during the scale and mature phase until 2025, to facilitate the scale-up phase. Secondly, quality control and measurement are an issue, which is present in the Netherlands on a low scale. The Netherlands follows International Organization for Standardization (ISO) guidelines for the quality check and frequency of checks. However, there is no regulated authority in place to perform the checks. This leads to the fact that HRS owners have the responsibility to ensure the ISO-required quality of fuel, and this is a very difficult, costly, and technically complicated process.

All in all, these barriers need to be removed by direct exemption from RED II and installing a well-organized local authority body ensures the frequency and quality of the fuel checks. This might take time, but removing these barriers will lead to faster growth in the FCET market.

2.5.3. Technical barriers

The energy efficiency of a FCET is a serious problem. Using renewable electricity to produce green hydrogen for FCETs is highly inefficient because between 57% and 73% of the energy is wasted compared to the pathway with BETs (Haugen et al., 2021). Groundbreaking innovative technologies might be needed to either find a way to reuse that 'lost' energy or to improve the energy efficiency in the engine of a FCET. However, there are technical thermodynamic limitations on the extent to which a FCET can improve its energy efficiency compared to the BET alternative (Haugen et al., 2021). Removing this barrier should thus be accomplished by both minimizing energy waste and increasing RES generation. Another important barrier is that for the production of fuel cells, platinum is needed which has a negative environmental impact (Miotti et al., 2017). If demand for FCETs significantly increases, more platinum will need to be produced, which implies that the total environmental impact of FCETs is negatively affected. Therefore, Miotti et al. (2017) argue that the use of platinum in fuel cell production should be minimized, along with achieving a high recycling rate of the platinum that is used.

2.5.4. Safety barriers

Another important barrier to hydrogen application is the safety procedures that come with delivering the fuel to the vehicles. In the Netherlands, a publication regarding hazardous materials (PGS35, 2020) has been established specifically for hydrogen delivery to vehicles. Some general dangers of gaseous hydrogen are; hydrogen has a very thin substance allowing it to penetrate through objects relatively easily, it has a high diffusion coefficient, very little energy is needed for ignition, and the flame of hydrogen is barely visible. Storing gaseous hydrogen in a pressurized tank can possibly lead to over-heated temperatures, and external damage to the tank might result in a seriously damaging explosion. Several components in HRSs are thus necessary to preserve the safety of implementing hydrogen. This includes a cooling system, a cascade system to control the difference in pressure between the tank and the vehicle, the dispenser must adhere to ISO standards, a purifier is needed to ensure a required percentage of purity of the hydrogen, and different measurement instruments must be in place (Parks et al., 2014). In PGS35 (2020), all these components are extensively discussed and HRS constructors must adhere to these regulations to minimize the risk of an explosion, that might not only be harmful to the station itself, but also to the society living around it. Moreover, all this equipment requires serious financial investments and comes with risks that might disincentivize potential HRS builders.

2.6. Contributions

This study builds further on existing literature, by using the SC-NC FRLM in multiple periods and applying this to an in-depth case study in the Northern Netherlands. This research has two main useful contributions; it considers the costs of an HRS in the FLRM, and the analysis is run for different points in the future with scenarios. The results are reflected upon by taking the identified barriers into account. As a result, a concrete roadmap for 2030, 2040, and 2050 is presented. This allows HRS investors, potential FCET buyers, and policy makers to observe how their decisions might play a part in the whole story.

3. METHODOLOGY

In this section, the methodology and design of this research will be discussed.

3.1. Model description

As mentioned before, the set-covering node capacitated flow refuelling location model (SC-NC FRLM) by Kluschke et al. (2020) will be used in this study. However, their model will be adapted and extended because their work also has its flaws. The adaptations are comprised of two main parts. First, following one of the future research suggestions by Kluschke et al. (2020), HRS costs are included in the objective function and minimized, which may provide clearer indications of necessary investments. Secondly, a future research recommendation was to include a temporal analysis to determine the HRS build-up over time. Kluschke et al. (2020) assumed a situation in 2050 where the objective is to cover 100% of heavy-duty truck flow with hydrogen as a transportation fuel. However, it is rather counter-intuitive to simply look at one point in time and assume that all heavy-duty road transportation is comprised of FCETs. It makes more sense to look at a gradually increasing percentage of FCETs on the road for different points in time and make the planning accordingly (Capar et al., 2013). This is done by introducing a FCET penetration percentage, which indicates the extent to which the HDT market is comprised of FCETs. In turn, this percentage reflects the demand for hydrogen that needs to be covered. A constraint that ensured that 100% of the flow should be covered (Kluschke et al., 2020) is now replaced with a constraint that ensures that at least FCET penetration percentage S is covered. Running the model in different years with different expected FCET penetration levels enables a temporal analysis to see how the HRS structure develops over time.

There are certain assumptions that the proposed model adheres to. These are partly based on those used by Kluschke et al. (2020). Some adaptations and new assumptions have been added, which are expressed in bold;

1. A vehicle drives along a single OD path that is determined as the shortest path from the closest highway entry junction of the origin area to the highway exit junction of the destination area.

2. The traffic volume on a single OD path is known in advance.

3. A station will only be located at one of the nodes that is part of the highway network.

4. The distance travelled is proportional to the fuel consumption.

5. The drivers have full knowledge about the location of the HRS along the path and refuel efficiently to complete a single trip.

6. **A FCET can cover 15 kilometres with 1 kg of H2, represented by the fuel efficiency p, equal to 15.**

7. **FCETs will drive to their destination and refuel at the latest station that they can reach on their OD path without running out of fuel.**

8. **The amount of fuel dispensed at an HRS is equal to the distance of the OD trip of the FCET, so that a vehicle starts and ends its trip with the same fuel level.**

9. HRS facilities cannot be located at a highway junction node.

10. **Each OD path has one potential HRS on the way, determined as the last station on its path.**

11. HRS facilities are capacitated.

12. **If an HRS is opened, all flow in kilometres along that node within supply capacity restrictions is served.**

Assumption (6) – (8) represent the refuelling process. FCETs in this research are assumed to drive as far as possible on their Origin – Destination path (henceforth; OD path) and refuel at the last station before arriving at their destination. Then, they refuel an amount of H2 that is equal to the length of the trip, so that the fuel level is equal at the start and end of the trip. As subsequent journeys are not considered, applying this assumption also prevents excessive refuelling and reflects the energy needed to cover the actual trips made on a daily basis (Kluschke et al., 2020). Then, the total hydrogen fuelled in a day reflects the total daily hydrogen demand. For instance -following the refuelling process- if a number of FCET trips pass along an HRS that have a total combined trip distance of 7500 kilometres, then at least 500 kg of H2 will be needed to cover the daily flow along that HRS.

The details of the mathematical model may be found in Appendix 5A.

4. CASE STUDY

To find an optimal HRS structure in a real-world setting, a case study is conducted in the Northern Netherlands (also referred to as NN). In this section, first the assumed FCET specifications are identified, after which the costs of building an HRS are determined. The relevant base parameter values are, then, identified. Next, the data collection procedure for the case study is explained. All information obtained serves as the basis for the scenario development, where the different parameter values in future scenarios will be explained.

The information and data required to implement the model in this case study are obtained directly from several reports, interviews, and publicly available information from companies in the transportation sector. OD flow data has been obtained from a dataset of the Central Bureau of Statistics (CBS). Furthermore, secondary information has been obtained from observations during an internship with an active partner in the HEAVENN consortium; Company A. This company has an operational HRS for passenger vehicles and is currently building an HRS facility for heavy-duty trucks.

4.1. FCET specifications

For the sake of comparability and standardisation, road vehicles are classified into different categories by the European Union. Through the literature review, interviews, and observations at Company A, it has become clear the advantage of FCETs increases with the range and weight of the vehicle. Hence, light- and medium-duty vehicles are less of interest when looking at hydrogen applications. N3 tractor-trailer combinations are the largest class of trucks in the Netherlands and have an average weight of 12 tons or more (TNO, 2013). Therefore, this category of trucks will be referred to as FCETs in the rest of the case study.

Hyzon Motors (2021), which is a rapidly growing FCET manufacturer with a subsidiary in the Northern Netherlands, currently produces FCETs with a range of 400-600 km. Hyundai (2021) developed the XCIENT FCET, which has a range of 400 km. In this study, a range of 400 km will be assumed. A project partner employs a fuel efficiency of 15 kilometres per kg of H2 which will be assumed in this study to calculate the flow in kilometres that can be served with one kilogram of H2.

Finally, hydrogen can be delivered to a FCET with either 350 or 700 bars of pressure. Heavy-duty vehicles usually have plenty of onboard storage capacity for hydrogen tanks, reducing the need for an expensive highly pressurised H2 tank to save space (Kast et al., 2018). Therefore, only 350 bar compressed hydrogen delivery for FCETs are addressed in this study. An overview of the assumed FCET specifications can be found in Table 2.

TABLE 2: FCET SPECIFICATIONS

N3 Heavy-duty trucks	***Quantity***	***Unit***

Weight	>12,000	Kg
Vehicle Range	400	Km
Fuel Efficiency	15	Km / kg H2
Tank pressure	350	Bar

4.2. HRS costs

In a project supported by New Energy Coalition, a fixed investment cost for Compressor, Storage, and Dispensing (CSD) costs of an HRS facility for FCETs was found to be 1.376 million euros. It concerns the extension of an existing light-duty vehicle HRS installation, and through consultation with the company it turned out that roughly an additional 1 million euros of Capex should be added to this amount, because a larger installation is needed and a more expensive buffer installation needs to be bought to account for the larger refuelling quantities. The costs were verified in an interview with another refuelling station company -which is in the HRS business and already has two operational HRS facilities in the Netherlands- who agreed that currently the total fixed costs of building an HRS for FCETs amount to roughly 2.4 million euros, which is assumed to be the fixed opening costs in the base case.

The variable costs in the case study relate to the supply costs of hydrogen. According to Company A, a price of 4 euros per kg of H2 is to be expected for the short term until 2030, which is assumed as a base case value and can be found in Table 3. This price is verified in a study by the Environmental Assessment Agency (PBL, 2020), which calculated a green hydrogen price ranging between €2,40 to €5,27 per kg in 2030, with a middle value of €3,83. Interviews show that the current supply price of H2 is between 6 and 8 euros, however they also confirm that a price of 4 euros per kg of H2 in 2030 would be realistic. In the model applied to the case study, the total annual hydrogen supply costs for an opened HRS will be calculated by multiplying the price of one kg of H2 with the daily flow served and the number of days a FCET operates annually.

TABLE 3: HRS COSTS IN THE BASE CASE

HRS Costs	**Euros**
Fixed opening costs	2,400,000
Variable hydrogen supply costs (p/kg)	4

4.3. Data Collection

The data that is required to perform the case study in this research is comprised of 5 parts. Firstly, the OD nodes are determined. Secondly, the arcs in the highway network of the NN are identified, after which the potential HRS facilities are located, followed by additional origin nodes from outside the region. Finally, the heavy-duty truck flow data on each of the paths are collected. These are discussed in the following sections.

4.3.1. OD nodes

The scope of this study is to locate HRS facilities in the Northern Netherlands based on heavy-duty truck flow between so-called NUTS3 regions. NUTS3 is a European geographical classification of regions within countries, to increase consistency and comparability between regions which allows for data analyses. NUTS3 is essentially a code, in which the first 2 letters indicate a country code, and the following numbers are specific regional identification numbers. For instance, NL113 is the NUTS3 code representing Groningen & surroundings. In this research, the main city in each NUTS3 region has been identified, and henceforth that specific NUTS3 region will be referred to with that city's name (see Table 4). The main highway junctions close to the OD node cities serve as connecting points in the highway structure and the latitude and longitude of those junctions have been stored as the set of highway nodes N. To connect all roads with nodes, four additional junctions were identified. The cities close to these junctions have been added to the set of nodes, but these will not be OD nodes. These cities are Hoogeveen, Zuidbroek, Beilen, and Heerenveen and have respectively been labelled with node IDs 11, 12, 13, and 14. All the nodes that connect the highway network are labelled as the set N and can be found in Appendix 5B. The set of OD nodes that refer to NUTS3 regions are a subset of N

and are labelled as set M. In Figure 1, the red symbols with city names represent the OD nodes, and the city names in green represent the connecting city junctions.

TABLE 4: SET OF OD NODES $\boldsymbol{M}$

Origin/ Destination	**NUTS3 Code**	**Node ID**
Winschoten	NL111	1
Delfzijl	NL112	2
Groningen	NL113	3
Leeuwarden	NL124	4
Sneek	NL125	5
Drachten	NL126	6
Assen	NL131	7
Emmen	NL132	8
Meppel	NL133	9
Zwolle	NL211	10
Randstad	**NLR**	**49**
Vlaanderen	**BE**	**50**
Nordrhein	**DENO**	**51**
Niedersachsen	**DENI**	**52**

FIGURE 1: COMPLETE HIGHWAY NETWORK

4.3.2. Highway Network

The next step is to identify the highway network in the NN on which FCETs drive to pick up and deliver orders between NUTS3 nodes. The main state-owned highways A7, A28, A32 and A37 have been embedded in the highway network. Because some NUTS3 regions cannot be reached only by A-highways, the N31, N33, and N381 have also been added to the highway network along which potential HRS facilities can be built. All highways that are part of the network are represented with green lines between the nodes in Figure 1. The arcs between every node form a set of directional arcs, which are necessary to determine the exact route a vehicle takes to reach its destination. Each arc is part of one of the highways from the complete network. The set of directional arcs, their lengths in kms and the highway they are located on can be found in Appendix 5E.

4.3.3. Potential HRS facilities

With the identification of OD nodes and the highway network, we determine the potential HRS locations for heavy-duty trucks. These locations are located on one of the highways and serve as connecting nodes so that the shortest path through a set of nodes can be calculated for each OD pair. Observations at Company A and interviews have shown that in practice not just every current gas station location can be considered a potential site for heavy-duty trucks. The large size of the trucks makes that manoeuvring around in the facility location towards a fuel dispenser and easily reaching the highway again is a serious burden that is often overlooked. Therefore, potential locations must be able to accommodate a substantial number of trucks per day. The National Dataportal Road Traffic (NDW) provides a nationwide map with large parking locations for heavy-duty trucks that are usually located at a gas station. When zooming in on the NN and looking at the highway network that was identified, a set of 34 potential facility locations have been identified. Following the refuelling process, only the last potential HRS site for each OD path is selected. This resulted in a filtered set of 23 potential HRS locations, which can be found in Appendix 5D. The remaining 11 parking locations are still part of the set N that connect the highway network however they are not considered as potential HRS sites. The complete highway network including potential HRS locations can be found in Figure 1.

The path for each OD combination can be determined now that the complete network has been identified. From a given origin, a FCET follows the directional arcs on the shortest path to its destination. The distance of each arc can be found in Appendix 5E. To illustrate how a path is determined and how the total trip distance has been calculated, consider a trip with the Origin in Groningen and the Destination in Leeuwarden. The associated path can be found in Table 5.

TABLE 5: EXAMPLE OD PATH

Node route	**3 → 43**	**43 → 6**	**6 → 45**	**45 → 4**
Arc ID	10	8	60	58
Arc length (km)	20	20	8	28
Total distance				**76**

In Figure 2, the example OD path is visualized. The purple line indicates the route, the purple numbers represent the arc ID, and the green numbers are the lengths in kilometres of the arcs.

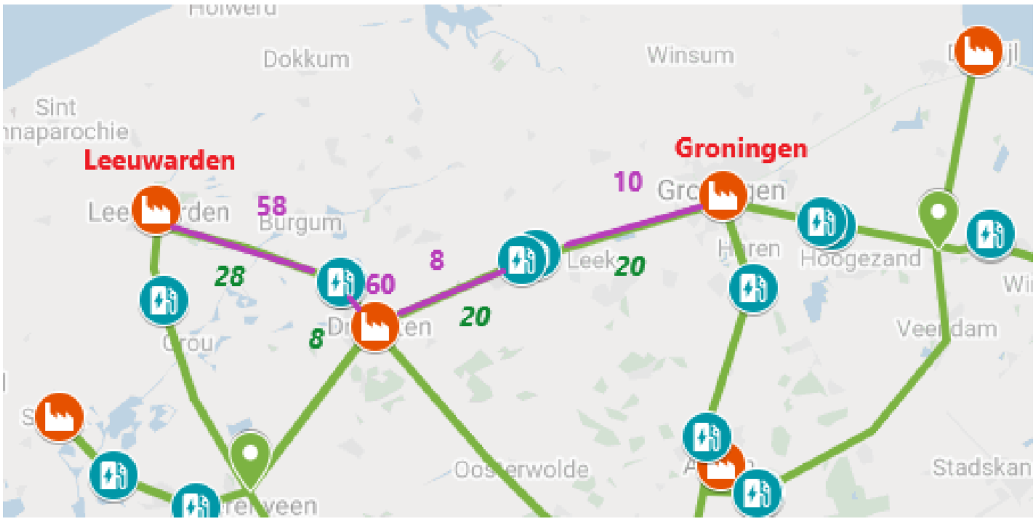

FIGURE 2: EXAMPLE OD PATH

4.3.4. Flows from regions outside the NN

Given the relatively low distances within the region, it is important to also include trips from outside the NN that have travelled a long distance and are likely to be needing hydrogen to end their trip with the same fuel level as at the origin. Neighbour countries and other large cities in the Netherlands should therefore be included. The selected regions are the Randstad (NLR) -which comprises the largest cities in the Netherlands in terms of economic activity-, Vlaanderen (BE), Nordrhein-Westfalen

(DENO) and an overarching region that combines Hamburg, Niedersachsen and Bremen labelled as Niedersachsen (DENI). They are labelled with a custom NUTS3 code, serving as a virtual node. The centre of these regions to a specific entering point in the highway network are the initial distance covered. After that, the vehicles follow the pre-generated path that corresponds with the route from the entering point to the NUTS3 destination in the network. The total distance of a trip from one of these regions to one of the destination nodes in NN is thus calculated as the sum of the initial distance to the entering node of the highway network and the subsequent distance from that entering node to the destination node. These regions and their entering point into the highway network can be found in Table 6. A visual overview of these regions can be found in Figure 3. The NUTS3 code and Node IDs can be found in Table 4, which are expressed in bold.

TABLE 6: ENTERING POINT OUTSIDE NN REGIONS

Origin	**Node ID**	**Entering Junction**	**Entering Highway**
Randstad (NLR)	14	Heerenveen	A7
Vlaanderen (BE)	14	Heerenveen	A7
Nordrhein-Westfalen (DENO)	10	Zwolle	A28
Niedersachsen (DENI)	1	Winschoten	A7

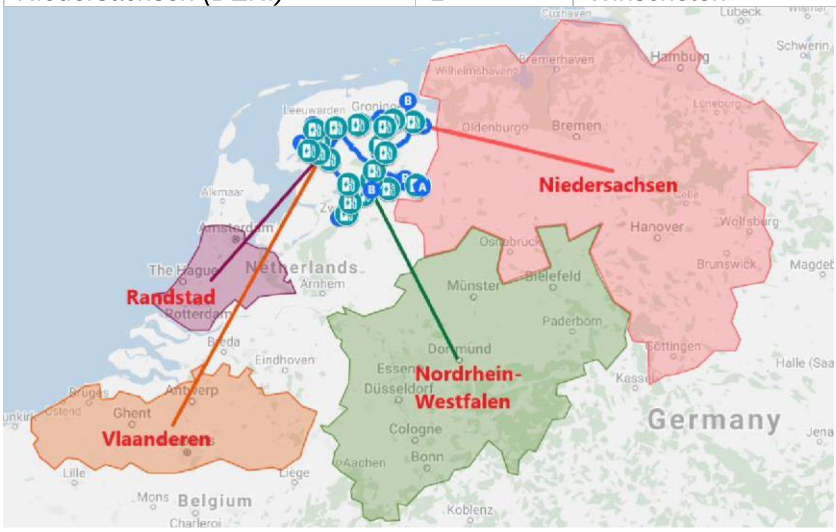

FIGURE 3: ORIGINS OUTSIDE NN

4.3.5. Heavy-duty truck flow data

The final piece of data needed is a representative set of trips between the identified OD pairs carried out by heavy-duty trucks. It is inherent to the FRLM that trip data for each path is needed to determine the flow on each of the arcs and along each potential HRS in the network. Through consultation at the KiM institution for Transport Policy, contacts at the Central Bureau of Statistics (CBS) have been acquired. After consultation and discussing the topic of this study, a dataset with all road traffic movements of tractor-trailer combinations in 2020 are provided. This dataset contains the annual flow in kilometres and number of trips from tractor and trailer trucks between NUTS3 origins and NUTS3 destinations both within the Netherlands and from origins outside of the Netherlands. Inter-zonal flows of heavy-duty, N3-class trucks that pass through the region of Northern Netherlands have been determined based on their Origin and Destination. Some important data exclusion steps had to be performed to fit the dataset within this research.

First, only trucks with a weight of over 12,000 kg had to be included. After consultation with the CBS, it turned out that 74% of the trips in the dataset was concerning N3 heavy-duty trucks. Secondly, only trips shorter than the vehicle range of 400 km had to be included, because of the assumption that longer trips will already have refuelled before reaching the NN, where their tank is already almost empty. Filtering the dataset on this requirement led to the selection of only some parts of Germany and Belgium. Moreover, trips shorter than 50 km were also excluded to prevent counting trips that only drive on small provincial roads. Finally, the data was provided for one year. To calculate daily heavy-duty truck movements, the total number of trips are divided by 260. This 260-day assumption stems from a sustainable transition study initiated by the Ministry of Infrastructure (2020). They based their study on the assumption that on average HDTs are in operation 260 days per year.

Figure 4 shows the daily HDT flows to a destination from all origins. The daily HDT flow is the daily number of trips multiplied with the distances of those trips. According to the refuelling logic, this means that these FCETs will demand more hydrogen to end the trip with the same fuel level. Zwolle clearly is the region to which most flow is directed. The second-largest destination is Emmen, after which the total flow is relatively equal to each destination.

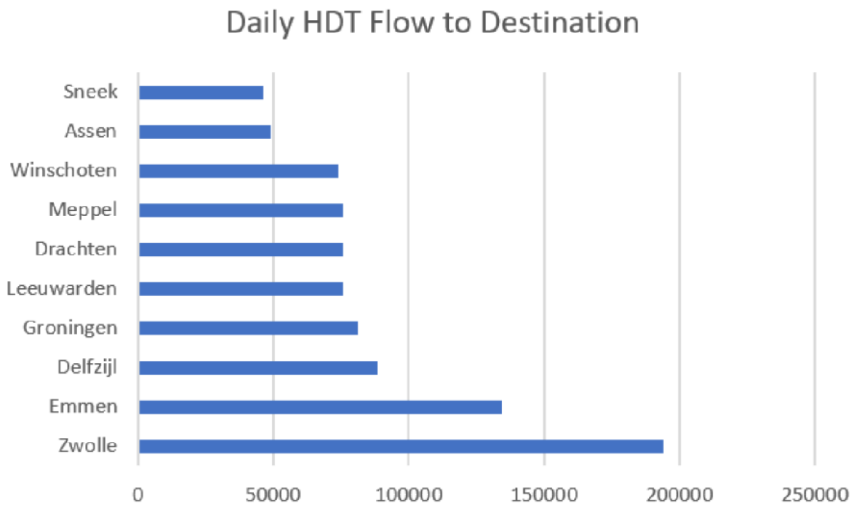

FIGURE 4: DAILY HDT FLOW

In Figure 5, the flow that passes through each HRS can be observed. This flow is the equivalent of the total volume of traffic flow along a node and is calculated by summing all the flow of the paths that pass through one of the potential HRS nodes. HRS node Haerst is located close to Zwolle and has the most flow passing through it. This can be explained by the fact that Zwolle is a large city that acts as a gateway to the NN. Also, a large part of the flow that originates from Germany enters the network there. Moreover, the daily HDT flow to Zwolle is the largest as can be seen in Figure 4. Bloksloot is another key node in the accessibility of the Northern Netherlands. The HRS at Bloksloot is located on the A7 near Heerenveen, which connects the Randstad and Vlaanderen with the highway network.

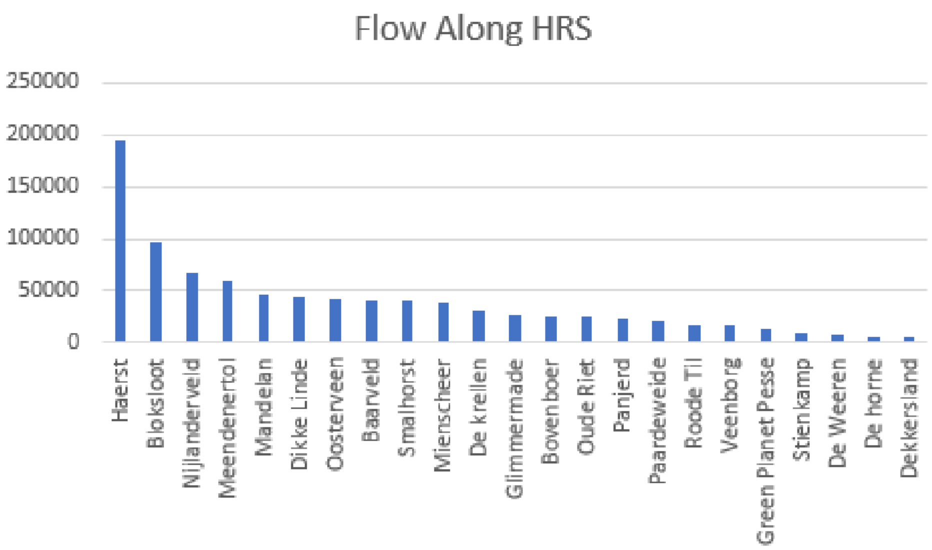

FIGURE 5: FLOW ALONG POTENTIAL HRS

4.4. Scenario Development

Because there is a lot of uncertainty about the development of hydrogen as an alternative transportation fuel, making accurate assumptions about future conditions is rather difficult. Therefore, scenarios are a good way of looking at various possible conditions and consequently observing their effects on the results. As the year of analysis reaches further in the future, it becomes harder to predict parameter values within more uncertainty. Therefore, the difference between the pessimistic, realistic, and optimistic scenarios increases to account for a broader range of possibilities. The realistic scenario in each year will serve as a base value, and the pessimistic and optimistic scenarios are symmetric deviations from those values.

In 2030, the base fixed station costs are 2,400,000 euros and the base variable hydrogen cost per kilogram is 4 euros (as described in section HRS costs 4.2) which can be found in Table 7. The base FCET penetration percentage is 10%. An interview with the Association B shows that the FCET market is expected to start 'taking off' around 2027/ 2028. It is not realistic to assume that the market is already mature by this time, so only 5% for the optimistic and pessimistic scenario is added or subtracted from the base percentage. A low number of electrolysers and a low RES availability is assumed in 2030. As a result, supply capacities at HRS stations are limited. This also has to do with the fact that pipelines will not yet be built or retrofitted to supply each HRS with hydrogen, and tube trailers can only carry up to 300-400 kg of H2 to the HRS (Singh et al., 2015). An assumption in 2030 is that at most two tube trailer trucks could be driving to an HRS each day if necessary, so the supply capacity limit is imposed at 750 kg per day.

TABLE 7: SCENARIO 2030

2030	**Fixed Assumption**	**Pessimistic**	**Realistic**	**Optimistic**
Supply Capacity limit	750 kg			
Type of Hydrogen	Blue & Green			
Hydrogen supply	Tube trailers			
FCET Penetration		5%	10%	15%
Fixed station cost		3,000,000	2,400,000	1,800,000
Hydrogen KG cost		4.5	4	3.5

After 2030, the introduction of pipelines and liquid hydrogen distribution is assumed to take off. Liquid hydrogen can be transported in trucks at much larger volumes than compressed gas and could become significantly cheaper than tube trailer distribution because the hydrogen does not require high compression costs (Singh et al., 2015). Singh et al. (2015) argue that a combination of tube trailers, pipelines, and liquid hydrogen could arise during different phases of FCET market development. This is confirmed in the 'Technology roadmap Hydrogen' of the International Energy Agency (IEA), in which is stated that from a cost perspective, gaseous tube trailer delivery of hydrogen is economically relevant at low levels of demand, liquid hydrogen delivery is preferable for larger capacities, and pipeline distribution is most efficient for very large hydrogen demand (Körner, 2015).

Therefore, from 2040 on, the assumption is made that liquid hydrogen distribution along with the development of pipelines will take over the supply of hydrogen to HRS facilities. In addition, the availability of green hydrogen increases as more electrolysers have been built, and they become bigger and more efficient. Therefore, the supply capacity limit is raised. Also, demand for hydrogen increases along with the FCET penetration percentage, which means that more capacity will be needed at the HRS facilities. Based on the former, a supply capacity limit of 1500 kg and a base hydrogen supply cost of 3 euros in 2040 is imposed, along with a fixed station cost of 1,500,000 euros which can be found in Table 8.

TABLE 8: 2040 SCENARIO

2040	**Fixed Assumption**	**Pessimistic**	**Realistic**	**Optimistic**
Supply Capacity limit	1500 kg			
Type of Hydrogen	Green			
Hydrogen supply	Liquid Hydrogen truck & Pipeline			
FCET Penetration		20%	30%	40%

Fixed station cost		2,000,000	1,500,000	1,000,000
Hydrogen KG cost		4	3	2

Finally, in 2050 the assumption is made that through technological advancements, economies of scale in green hydrogen production, and large FCET demand growth, the market has reached a mature stage. Liquid hydrogen is assumed not to be necessary anymore and most of the hydrogen will be supplied through the extensive pipeline network at low costs. Therefore, the supply capacity limit is raised to 2500 kg and a base hydrogen supply cost of 2.5 euros is imposed, along with a fixed station cost of 1,000,000 euros as can be seen in Table 9.

TABLE 9: 2050 SCENARIO

2050	**Fixed Assumption**	**Pessimistic**	**Realistic**	**Optimistic**
Supply Capacity limit	2500 kg			
Type of Hydrogen	Green			
Hydrogen supply	Pipeline			
FCET Penetration		40%	60%	80%
Fixed station cost		1,500,000	1,000,000	500,000
Hydrogen KG cost		3.5	2.5	1.5

5. RESULTS

In this section, the results and output of the model – which have been implemented with the Excel Solver - are outlined. First, the results of the pre-specified scenarios are discussed, after which several sensitivity analyses are elaborated on.

5.1. Scenario results

The first analysis of results will be made on the specific scenarios formulated in the case study. For the years 2030, 2040, and 2050 a pessimistic, realistic and optimistic scenario was presented. The results of each year are first separately discussed, after which a brief conclusion is drawn.

5.1.1. Results 2030

In 2030, a capacity limit of 750 kg is imposed, therefore the variable supply costs for one station are limited to that threshold. The results can be found in Table 10. We observe that the fixed opening costs are significantly higher than variable supply costs in all scenarios for 2030. This can also clearly be seen in Figure 6. The variable hydrogen supply costs are still relatively high and tube trailer delivery is the only supply option for this case. Another observation is that the average capacity is equal to the capacity limit. This could be explained by the fact that it is more cost-efficient to have large capacities at the station because more flow can be captured and in total less fixed station opening costs will have to be incurred.

TABLE 10: RESULTS 2030 SCENARIO

2030	**FCET penetration**	**Number of Stations**	**Average Capacity**	**Fixed opening cost**	**Hydrogen supply costs**	**Total costs**
Pessimistic	5%	4	750	12,000,000	3,556,800	15,556,800
Realistic	10%	8	750	19,200,000	6,323,200	25,523,200
Optimistic	15%	12	750	21,600,000	8,299,200	29,899,200

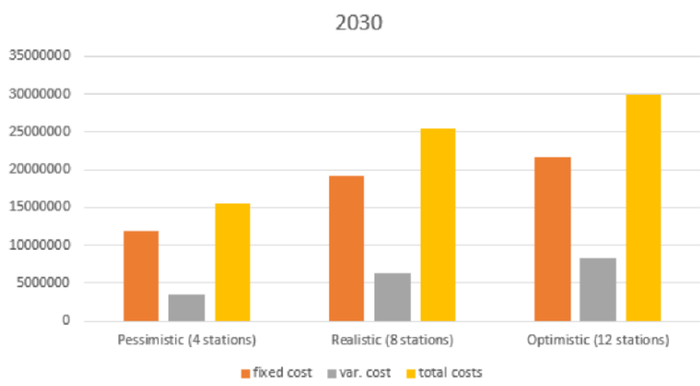

FIGURE 6: RESULTS SCENARIO 2030
2030

FIGURE 7: HRS LOCATIONS

5.1.2. Results 2040

In 2040, the number of stations increases with the growth of the economy. The FCET penetration percentage is significantly higher than in 2030, which means that demand for hydrogen is increasing, and the market has reached a phase where scale economies emerge. The results are displayed in Table 11. The consequences of economies of scale can also be seen in the total costs. The total costs of the realistic scenario amount to approximately 32M euros and the costs of the realistic scenario in 2030 were 25M euros, whereas the FCET penetration has tripled (from 10% to 30%). This cost reduction per station indicates that the economic burden around HRS facilities weakens, and therefore more FCETs can be refueled with hydrogen.

TABLE 11: RESULTS 2040 SCENARIO

2040	**FCET penetration**	**Number of Stations**	**Average Capacity**	**Fixed opening cost**	**Hydrogen supply costs**	**Total costs**
Pessimistic	20%	8	1500	16,000,000	12,438,400	28,438,400
Realistic	30%	12	1500	18,000,000	14,008,800	32,008,800
Optimistic	40%	16	1500	16,000,000	12,459,200	28,459,200

Looking at the relative amount of fixed and variable costs in Table 11, clearly, the variable costs are almost equal to the fixed costs. Although the variable supply costs decrease compared to 2030, the fixed costs significantly decrease as well, and the stations now have larger capacities due to the introduction of pipeline distribution and liquid hydrogen supply. Larger capacity implies that more hydrogen needs to be supplied, thereby increasing the variable costs. The locations of the HRS that are opened in the realistic scenario of 2040 can be seen in Figure 8. Again, three stations around Groningen are opened, however an increasing number of stations emerge around other cities such as Zwolle and Leeuwarden.

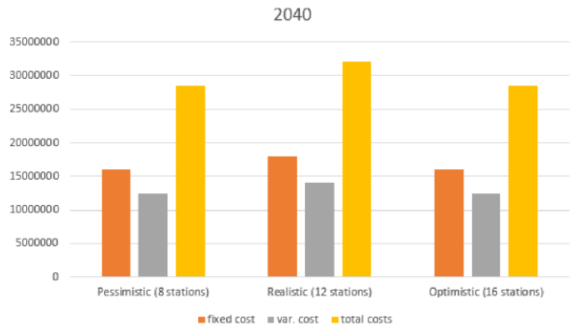

FIGURE 8: RESULTS SCENARIO 2040

FIGURE 9: HRS LOCATIONS 2040

5.1.3. Results 2050

In 2050, the FCET market is assumed to have matured completely. In the realistic scenario, 60% of all HDT flow is replaced with FCETs, and the fixed opening costs and variably supply costs have significantly dropped. Additionally, there is a widespread pipeline network that can distribute hydrogen throughout the NN efficiently and at a low cost, which also means that the availability of hydrogen has increased. The results for 2050 can be found in Table 12. The model aims to minimize total costs and therefore will try to cover as much demand as possible from one station to prevent paying the substantial fixed opening costs for a new station. In 2030 and 2040 this led to the fact that the capacity of the HRS was equal to the supply capacity limit. However, in 2050 this is not the case anymore because variable costs are considerably higher than the fixed costs which can be seen in Figure 10. Also, because of the high FCET percentage that must be covered, HRS facilities in locations with a low amount of flow are now being built. In earlier years, it was not financially viable to place HRS facilities there.

TABLE 12: RESULTS 2050 SCENARIO

2050	**FCET penetration**	**Number of Stations**	**Average Capacity**	**Fixed opening cost**	**Hydrogen supply costs**	**Total costs**
Pessimistic	40%	10	2460	15,000,000	22,322,300	37,322,300
Realistic	60%	17	2120	17,000,000	23,413,000	40,413,000
*Optimistic**	80%*	26*	1760*	13,000,000*	18,665,400*	31,665,400*

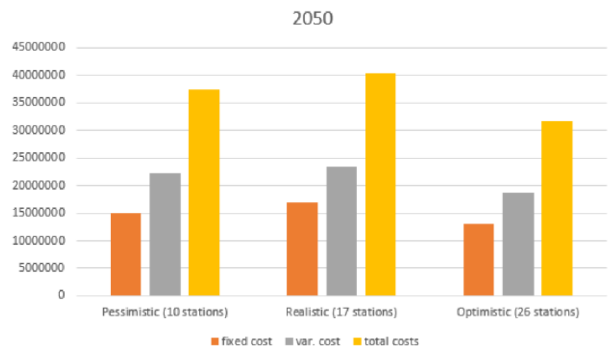

FIGURE 10: SCENARIO RESULTS 2050

FIGURE 11: HRS LOCATIONS 2050

An important note is that in the optimistic scenario of 2050, the selected set of potential HRS locations was not sufficient to cover an 80% FCET penetration percentage within capacity restrictions. Therefore, three HRS facilities from the initial set that were not selected as the last HRS on each OD path were manually included. The HRS that were selected were chosen as the closest nodes to the HRS along which the most flow was not covered due to the capacity limit. The selected stations were Laageveen, Peelerveld and Dorpshellen with respective node IDs 24, 28 and 40.

The locational results of the realistic scenario of 2050 can be seen in Figure 11. 17 HRS facilities have now been opened and they are widely dispersed throughout the region. An average capacity of 2120 kg is enough to cover 60% of the HDT flow. Transportation companies driving from one of the origins to another destination will now have at least one HRS on their path, which means that the uncertainty of not being sure where to fuel along the way is taken away.

5.1.4. Scenario analysis conclusion

In early adoption years, three large HRS facilities should be built close to Groningen and five HRS facilities throughout the rest of the NN. Eight stations with a capacity of 750 kg will suffice to cover a FCET penetration percentage of 10%. In 2040, fixed costs are assumed to drop, and new stations should be built that are more dispersed in the NN. Due to increased RES availability and economies of scale in H2 production, larger capacities can be assumed, and therefore 12 large stations with a capacity of 1500 kg a day will be able to cover a FCET penetration percentage of 30%. Finally, in 2050 the hydrogen market is assumed to have matured, and the supply cost of hydrogen has dropped significantly. In the realistic scenario, 60% of all trucks are FCETs and 17 stations with an average capacity of 2120 kg a day will be able to cover that percentage. The stations are mainly clustered around the four largest cities in the NN; Groningen, Zwolle, Assen, and Leeuwarden.

5.2. Sensitivity analysis

Sensitivity analyses are useful to see how a model reacts to changes in assumptions and parameters. In this study, three types of sensitivity analyses will be performed. First, a budget limit is imposed into the model, thereby placing an upper bound on the amount of total costs. Secondly, the capacity restrictions in the base model are lifted, to see if and how the structure and total costs of the HRS network can be improved. Finally, the assumption that only HDT flow within the NN needs to be covered is tested. The parameters and assumptions that are not affected by the sensitivity analyses will remain the same as in the realistic scenarios.

5.2.1. Budget Limit

In the light of the decarbonisation of the transportation sector, it might also be interesting to look at how the FCET coverage is affected by a budget limit. This can be specifically useful if, for instance, the government sets out a specific budget that can be allocated to build a number of HRS sites. Obviously, the aim of a government budget like this is to cover as much FCET flow as possible. Thus, instead of limiting the service level as in the base model, we test to maximize the covered service level by a HRS given a budget limit. Budget limits like these are specifically interesting in the early years of FCET adoption. When a mature market phase has been reached, governments are not likely to incentivize building HRS with large subsidies, because the market will be self-sufficient. Therefore, this sensitivity analysis was only performed for 2030 and 2040. The results can be found in Table 13 and 14.

TABLE 13: BUDGET LIMIT SENSITIVITY 2030

2030 Realistic	**Budget Limit L**	**FCET coverage**	**Number of Stations**
	10,000,000	3.77%	3
	30,000,000	11.31%	9
	50,000,000	18.85%*	15

TABLE 14: BUDGET LIMIT SENSITIVITY 2040

2040 Realistic	**Budget Limit L**	**FCET coverage**	**Number of Stations**
	30,000,000	27.64%	11
	50,000,000	45.51%	19
	70,000,000	48.83%*	23*

An important conclusion that can be drawn from the results of this sensitivity analysis is that with the same budget, more coverage and thus more stations can be built in 2040 compared to 2030. This has to do with the expectancy that prices are likely to drop over time as the market matures. However, by 2040, it will be cheaper to build HRS facilities and capacity limits are higher. Consequently, this reduces the need for the government to step in and make it financially attractive to build an HRS. Specifically, in early adoption years, the government plays an essential role in incentivizing entrepreneurs to make the investment, which in turn incentivizes transportation companies to invest in FCETs. In 2030, a budget of 30,000,000 euros could already be sufficient to build an HRS infrastructure that can build 9 HRS facilities that can supply 11.31% of all HDT flow in the NN with hydrogen for their FCETs.

5.2.2. No capacity restrictions

Another parameter that is important to check for sensitivity is the capacity limit. What if there is no capacity constraint at all? The principles of the model and its assumptions will already answer this question partly; the model will try to open as little stations as possible by only opening the HRS with the most flow along it. However, this does not say anything about the related costs and how much costs can be saved. The results in Table 15, Table 16, and Table 17 were obtained if there is no capacity limit at all.

A few interesting comments can be made based on these results. Relieving the capacity limit significantly reduces HRS building costs in every scenario. The reason that the capacity limits were imposed in the first place was that it is not reasonable to assume that an HRS has infinite capacity, given the limited availability of green hydrogen and the supply restrictions of tube trailers. Through the interviews and observations, it became clear that in 2030 a daily capacity of 750 kg is reasonable, and 1000 kg is the absolute maximum. Another observation is that the percentual cost reduction because of the capacity limit exclusion decreases over time. Whereas in 2030, 57% of the total costs could be reduced, in 2050 this is only 25%. With no capacity restrictions in 2030, the model would open two stations with an average capacity of almost 3000 kg. Therefore, the main takeaway is that capacities should be as large as possible to reduce costs, especially in early adoption years, but within realistic availability boundaries. The initial availability boundaries underline the importance of immediate scale-up of green hydrogen production.

TABLE 15: NO CAPACITY RESTRICTIONS 2030

2030 realistic	**# of stations**	**Average Capacity**	**Total cost**	**Cost reduction**
With capacity limit	8	750	25,523,200	
Without capacity limit	2	2995	11,029,600	
Absolute savings				**14,493,600**
Absolute savings				**57%**

TABLE 16: NO CAPACITY RESTRICTIONS 2040

2040 realistic	**# of stations**	**Average Capacity**	**Total cost**	**Cost reduction**
With capacity limit	12	1500	32,008,800	
Without capacity limit	3	5580	17,549,400	
Absolute savings				**14,459,400**
Absolute savings				**45%**

TABLE 17: NO CAPACITY RESTRICTIONS 2050

2040 realistic	**# of stations**	**Average Capacity**	**Total cost**	**Cost reduction**
With capacity limit	17	2120	54,460,800	
Without capacity limit	6	5560	40,694,400	
Absolute savings				**13,766,400**
Absolute savings				**25%**

5.2.3. Only Trips in Northern Netherlands

The third and last sensitivity analysis that has been performed is to only include trips within the NN. In the light of the HEAVENN, in which the goal is to create a circular, integrated hydrogen economy in the NN, this might be specifically interesting. In addition, Upchurch et al (2009) state that a relatively self-contained study area, with minimal flows to or from other regions would be desirable, especially in early HRS roll-out stages. The results can be found in Table 18.

TABLE 18: ONLY TRIPS INSIDE NN

Only NN Trips	**FCET penetration**	**Number of Stations**	**Average Capacity**	**Fixed opening cost**	**Hydrogen supply costs**	**Total costs**
2030	10%	4	590	9,600,000	2,444,000	12,044,000
2040	30%	5	1400	7,500,000	5,444,400	12,944,400
2050	60%	7	1990	7,000,000	9,028,500	16,028,500

In line with expectation, the total number of stations required to cover different percentages of FCET penetration is significantly lower than in the initial scenario results. There are no FCETs anymore that have travelled a long distance and need a lot of hydrogen to end their trip with the same fuel level. A total government investment budget of approximately 12,000,000 euros could be enough to cover 10% of the HDT flows inside the NN in 2030. This is a substantial amount of money, however it could contribute significantly to creating a self-sustaining hydrogen economy in the NN by incentivizing transportation companies to invest in FCETs and taking the economic burden of expensive HRS facilities away.

6. DISCUSSION

In this section, an extensive discussion on the results of this research is provided. This is important to reflect on the findings, and to link the results to the barriers presented in the theoretical background. Interviews have been conducted to reflect on the results and to discuss the practical implications.

6.1. Economic barriers

The economic barriers identified were mainly comprised of three elements: the high price of FCETs, the high costs of building an HRS, and the high supply cost of green hydrogen. Also, conventional fuels have continued to be abundantly available at low costs. The results of this study have shown that the total costs of building an HRS infrastructure strongly decline over time. When discussing these results in interviews, some important comments were made. One of the interviewees mentioned that the fixed investment costs in the base scenario were correct, however the interviewee did not agree with the pace at which these costs go down over time. Some cost reductions can be expected due to more efficient compressors, higher availability of required materials, and scale economies, however the entire installation will still be very costly. Also, when a station becomes larger, more compressors are needed and fixed costs could actually increase. On the other end, the interviewee mentioned that developments around liquid hydrogen distribution in Germany are promising, and this might actually bring the fixed building costs of an HRS down significantly because there is no need for an expensive compressor in that case. The expectation that the variable hydrogen supply costs decline strongly over time was confirmed. Through increasing availability of excess RES, and the introduction of retrofitted pipeline structures, costs will most likely fall rapidly. Although the pipeline transportation costs are considerably lower than tube-trailer delivery, two important notes should be made. First, one of the interviewees made the point that pipelines are usually not directly connected to gas stations, especially not along the highway. The question is whether the total distribution costs are still lower if the pipeline infrastructure must be rebuilt so that the hydrogen can be directly delivered to HRS facilities along the highway. Secondly, the initial investment costs of building pipelines from scratch are very expensive. Apostolou et al. (2019) found that these costs range between 400,000 and 3,200,000 euros per km of pipeline. The advantage of the Northern Netherlands is the gas pipeline structures that are already in place which can potentially be retrofitted to transport hydrogen, thereby avoiding the high initial building costs, and making an extensive hydrogen pipeline network more realistic in the future. Although it is not clear which distribution method will become dominant, the economic barriers around supply, investment, and dispensing costs of hydrogen at an HRS were expected to come down significantly, which is in line with the findings of this research.

6.2. Regulatory barriers

One of the most urging regulatory barriers identified was the absence of a Guarantee of Origin (GoO) of green hydrogen. A GoO would enable companies to easily show and prove to the public that they are working with certified green hydrogen. This 'green tag' of hydrogen could play an important role in the long term. However, the observations showed that it is currently more important to build the hydrogen economy 'blueprint', and then the focus can be shifted on the Green tag. For a lot of companies, the absolute base requirement is to stay financially healthy, which is simply not possible at this point, with only green hydrogen and no governmental support. An important additional regulatory barrier that became clear through interviews is that it is very difficult and expensive for an HRS investor to obtain the right permits to build an HRS. Almost all HRS that are currently operational have mainly been realized through experimentational projects funded by the government and through subsidies. Local governments often barely know what hydrogen exactly is and therefore the procedure is very time-consuming and complex. Due to the uncertainty and lack of guidelines, it is also extremely difficult to convince stakeholders that the investment is financially responsible and will pay off within a given timeframe. In 2021, the total budget available for subsidies in the energy transition (not only specifically for the HRS roll-out) was 20,000,000 euros. A total of 80,000,000 euros of subsidy was requested, which means that a lot of requests were turned down. These setbacks certainly do not help the promotion of HRS and FCETs. Therefore, the interviewee confirmed that the results of this study are useful to get a grasp of how much money is needed to cover a certain FCET percentage. For instance, the budget limit sensitivity analyses showed with a government investment of 30,000,000 euros, a FCET coverage of 11.31% in 2030 can already be achieved by building 9 HRS facilities in the NN. As an illustration; for the rise of battery electric vehicles, public and private funding were also key to promotion and widespread usage. Where there were only 4042 light-duty BEVs on the road in 2010, today there are more than 179,000 BEVs on the road in Europe (EAFO, 2020). Similarly, when the potential of oil and natural gas was noticed, enormous financial resources were allocated for the commercialization of these energy sources. It was more a politico-economic policy and funding rather than market functioning on its own which brought oil and natural gas to its present state (Singh et al., 2015). Thus, market functioning on its own will not be able to facilitate the widespread usage of hydrogen in the transportation section. Regulatory standards are required that ensure the alignment of both market signals and strong market instruments as they become tighter over time (Bednar-Friedl et al., 2015). A relevant quote from the interviews illustrates this; "*More knowledge, guidelines, and expertise are quickly needed to take away uncertainty and doubt and allow companies to make investments with confidence."*. Finally, it was stressed that the chicken-and-egg problem (see Introduction) should be approached chain-wide, rather than looking at different parts in the chain.

6.3. Technical barriers

The energy efficiency of FCETs was another barrier to FCET adoption. An interviewee at the Association B mentioned that the business case for FCETs is far from closed compared to BETs. Transportation companies will rather look at making efficiency improvements for BETs and use the available RES optimally directly, than paying a high price for the conversion to hydrogen where around 50% of the energy gets lost in the process. Moreover, the interviewee argued that if a technological breakthrough in BET range and charging time prevails, such as battery swapping technology, this might completely change the playing field. To nuance that perspective, another interviewee mentioned that there are also developments around using the 'lost' energy of hydrogen for FCETs to heat local greenhouses or other premises that need heating in a smart system. Also, fuel efficiency improvements could decrease the gravity of this barrier. In addition, the interviewee mentioned that at some point the fluctuations in RES availability will mean that energy efficiency is not a costly problem anymore. Finally, this interviewee mentioned that BETs also come with dangers and challenges because lithium-ion batteries are needed for BETs, and explosion risks are relatively high. The raw materials needed to produce those batteries are also scarce and long charging times along with short driving ranges should not be overlooked. An important note that was made by both interviewees is that BETs will not be able to develop without FCETs, and the other way around. They complement each other, and the extent to which one outperforms the other completely depends on technological innovations and the availability of their required materials. Both technologies should thus be promoted and constantly improved because obviously, the essential, overarching goal is to work towards an emission-free future.

6.4. Operational barriers

In addition to the barriers identified in the theoretical background, another set of operational barriers was identified through the process of conducting this study. An interesting note that was made in the interviews, is the fact that fuelling stations along the highway work with concessions. Essentially, the owner of the highway sets out bids, and then companies can make a bid to build a fuelling station at a specific location. These permits usually last for 8 to 10 years. This means that additional costs will be incurred to obtain the rights to build an HRS at an existing highway location. Building an HRS from scratch at a new location somewhere along the highway is even more expensive and often not allowed due to residential areas nearby. Therefore, in the next 10 years building the HRS facilities should be realised by existing companies with a running permit. Gas stations that are currently located along the highway should have an interest in working with alternative fuels. If governments indeed provide more subsidies and incentivize the roll-out of HRS stations, it should be the large, existing gas stations that make the first jump. Once these HRS facilities have been built and existing permits expire, the government should prioritize companies that intend to build HRS facilities in the process of granting concessions. This way, conventional gas stations are gradually ruled out and there is more room and incentives for HRS investors.

A second operational barrier mentioned in the interviews is that even if 10 or 30% of all HDTs are FCETs and these can theoretically be covered by a given number of stations, there are still paths that are not covered. In that case, FCETs must deviate from their route to find an HRS. Deviating from a route is very costly for transportation companies, because margins are already extremely low. Therefore, it became apparent that an increasing number of companies would prefer to place an HRS at the home location. These so-called 'small-scale' HRS facilities cost around 300,000 euros, so it is a serious investment. The fuelling time is considerably longer, and the required permits and procedures are endless. However, it takes away the burden of having to fuel along the route, which also costs money. Also, if a company owns multiple FCETs, the investment cost per truck declines. Moreover, if regulation and permit guidelines become clearer and less complex, this might be a viable option for large transportation companies. The interviewee expects this type of HRS facilities to emerge alongside the public HRS in the long term.

6.5. Managerial implications

All in all, some important managerial implications can be extracted from the findings and discussion of this study. First and foremost, the role of the government in making the FCET market 'take off' is essential. The literature, interviews, and observations made it clear that without government support, it will not be possible to create a self-sufficient market in the long term. The role of an accommodating HRS structure where transportation companies can refuel their FCETs with certainty is essential. Through the presented model and its results, it was found that a government investment of 30,000,000 euros could already be enough to build 9 HRS facilities for FCETs by 2030, which could cover approximately 12% of all HDT flow through the NN. In 2040 and 2050 less money would be needed to realise new HRS facilities, however by then, the market should be able to keep building and extending the initial HRS structure without government support. The exact numbers and locations might not be correct, however the uncertainty around hydrogen in transportation makes that no model can accurately predict future requirements. It is more the underlying pattern that indicates that strong action is needed now, to bring the market about in the future. The second implication is that the capacity of stations in early years should be as large as possible. In the adoption phase of FCETs and HRS facilities, it is a lot cheaper to build a few large stations, than to build numerous small stations because fixed costs are extremely high. HRS investors should transparently communicate announcements to the local transportation sector if they decide to make the investment and start building an HRS facility. This takes the integral uncertainty away and incentivizes companies to invest in FCETs. From now until 2030, collaboration, guidelines, and transparency are key. From 2030 to 2040, the government should keep a mediating role between the FCET market and HRS investors, as technological developments allow for more economies of scale and efficiency improvements. From 2040 onwards, the FCET market should be self-sufficient, and government involvement is not needed anymore. A widespread HRS network along the highway is possible and it can be complemented with smaller stations at the home location of companies. In this way, the FCET market could significantly contribute to decarbonising the transportation sector. In Figure 12, a concise roadmap with the main steps needed to achieve this can be found.

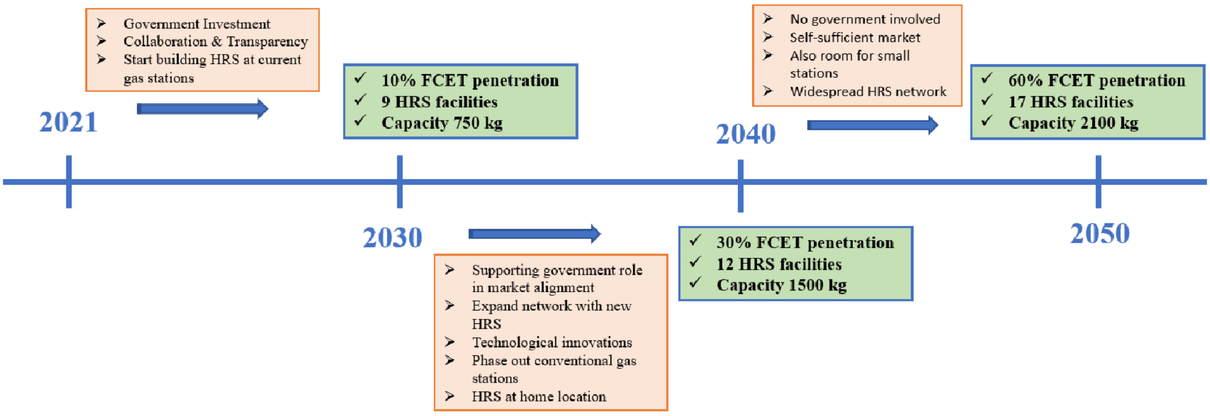

FIGURE 12: ROADMAP TOWARDS 2050

7. CONCLUSIONS

In this study, the development of an HRS network to accommodate FCETs has been identified. Through an extensive literature review, it became apparent that there is a lack of research on HRS structures for FCETs. There was only one article that addressed this problem, however cost aspects were not included in the analysis, and the study was only aimed at one point in time. The FRLM was extended in this research by taking those aspects into account and applying the model to a case study in the Northern Netherlands. The results and discussion made clear that the HRS roll-out in the Northern Netherlands should be initiated by building large HRS facilities along the highway network at existing gas stations close to major cities in the Northern Netherlands. Supply capacity restrictions ease over time as the availability of green hydrogen increases and a hydrogen pipeline network is built. Moving towards the future, current refuelling location permits will expire, and new HRS facilities can be built, thereby extending the HRS network. From the discussion, it became clear that the role of the government is essential in the first phase. Clear guidelines, regulations, subsidies, and investments are key to make the FCET and HRS market economically viable.

7.1. Limitations

Several limitations in this research can be identified. First, this research solely looks at an HRS infrastructure for heavy-duty FCETs. The determination of the number and location of HRS facilities is only based on HDT flow. However, medium- and light-duty fuel cell vehicles could also make their way into the market over time. This could have significant implications on the required HRS structure in terms of locations and capacities. Secondly, only some regions from outside the Northern Netherlands have been selected as additional origins, which might lead to incomplete flow data on the identified highway network. Third, the refueling process for HDTs assumes that only the amount of hydrogen equal to the length of the OD trip is fueled. However, it might be more realistic to assume that each vehicle completely fills its tank, irrespective of the trip length. Finally, vehicle range is not extensively taken into consideration given the small size of the study area. However, if the model is implemented in larger areas, increasing vehicle ranges might have implications for the required HRS infrastructure.

7.2. Future research

This study concludes with two main future research suggestions. First, research into a widespread hydrogen pipeline infrastructure that can deliver hydrogen directly to HRS facilities along the highway is needed. From the discussion it became clear that pipeline investment costs are very high, specifically if new connections to stations along the highway should be built. An integrated long-term financial assessment should be made, and the possibilities of centrally located ‘depots’ with compressed hydrogen close to a cluster of HRS facilities could be interesting. Another important future research suggestion is to dive deeper into the possibility of on-site green hydrogen production at the HRS. Supply costs would most likely be much lower, but the total investment costs and the daily capacity that can be achieved are interesting factors to look at. Then, the trade-off can be made; is it cheaper and more efficient in the long-term to have centrally located HRS facilities, or a decentralised structure in which numerous small self-sufficient HRS are located?

REFERENCES

Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy*, *123*, 280–288. https://doi.org/10.1016/j.enpol.2018.08.063

Anandarajah, G., McDowall, W., & Ekins, P. (2013). Decarbonising road transport with hydrogen and electricity: Long term global technology learning scenarios. *International Journal of Hydrogen Energy*, *38*(8), 3419–3432. https://doi.org/10.1016/j.ijhydene.2012.12.110

Apostolou, D., & Xydis, G. (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. In *Renewable and Sustainable Energy Reviews* (Vol. 113). Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109292

Bednar-Friedl, B., Wolkinger, B., König, M., Bachner, G., Formayer, H., Offenthaler, I., & Leitner, M. (2015). Transport. In *Springer Climate* (pp. 279–300). https://doi.org/10.1007/978-3-319-12457-5_15

Burkhardt, J., Patyk, A., Tanguy, P., & Retzke, C. (2016). Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply. Applied Energy, 181, 54–64. https://doi.org/10.1016/j.apenergy.2016.07.104

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2019). Fuel cell electric vehicles: An option to decarbonize heavy-duty transport? Results from a Swiss case-study. Transportation Research Part D: Transport and Environment, 70, 35–48. https://doi.org/10.1016/j.trd.2019.03.004

Capar, I., Kuby, M., Leon, V. J., & Tsai, Y. J. (2013). An arc cover-path-cover formulation and strategic analysis of alternative-fuel station locations. European Journal of Operational Research, 227(1), 142–151. https://doi.org/10.1016/j.ejor.2012.11.033

EAFO. (2020). EAFO. European Alternative Fuels Observatory. https://www.eafo.eu/vehicles-and-fleet/n2-n3

EC. (2014). Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure. Official Journal of the European Union, 2014(October), 20. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN

Forrest, K., Mac Kinnon, M., Tarroja, B., & Samuelsen, S. (2020). Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Applied Energy, 276. https://doi.org/10.1016/j.apenergy.2020.115439

H2 Station Maps. (2020). COSTS AND FINANCING | H2 Station Maps. https://h2stationmaps.com/costs-and-financing

Hall, D., & Lutsey, N. (2019). Estimating the infrastructure needs and costs for the launch of zero-emission trucks. International Council on Clean Transportation. https://www.researchgate.net/publication/335104931_Estimating_the_infrastructure_needs_and_costs_for_the_launch_of_zero-emission_trucks

Haugen, M. J., Paoli, L., Cullen, J., Cebon, D., & Boies, A. M. (2021). A fork in the road: Which energy pathway offers the greatest energy efficiency and CO2 reduction potential for low-carbon vehicles? Applied Energy, 283, 116295. https://doi.org/10.1016/j.apenergy.2020.116295

Hodgson, M. J. (1990). A Flow-Capturing Location-Allocation Model. Geographical Analysis, 22(3), 270–279. https://doi.org/10.1111/j.1538-4632.1990.tb00210.x

HyLaw. (2021). HyLaw Online Database: National policy papers. https://www.hylaw.eu/database#/database/hydrogen-as-a-fuel-and-refueling-infrastructure-for-mobility-purposes

Hyundai. (2021). XCIENT Fuel Cell | HYUNDAI Truck & Bus. https://trucknbus.hyundai.com/global/en/products/truck/xcient-fuel-cell

Hyzon. (2021). Heavy Duty Trucks | Zero emission, hydrogen-powered | HYZON Motors. https://hyzonmotors.com/vehicle/heavy-duty-trucks/

IEA. (2019). Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030. https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030

International Energy Agency. (2020). The Netherlands 2020 Energy Policy Review. In International Energy Agency. www.iea.org/t&c/

Isaac, N., & Saha, A. K. (2021). Analysis of refueling behavior of hydrogen fuel vehicles through a stochastic model using Markov Chain Process. Renewable and Sustainable Energy Reviews, 141, 110761. https://doi.org/10.1016/j.rser.2021.110761

Kast, J., Morrison, G., Gangloff, J. J., Vijayagopal, R., & Marcinkoski, J. (2018). Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market. Research in Transportation Economics, 70, 139–147. https://doi.org/10.1016/j.retrec.2017.07.006

Körner, A. (2015). Technology Roadmap Hydrogen and Fuel Cells Technical Annex. In International Energy Agency (IEA). http://www.g20ys.org/upload/auto/1888e90ef287bf674665cd8b97fffcc45164b928.pdf

Kuby, M., & Lim, S. (2005). The flow-refueling location problem for alternative-fuel vehicles. Socio-Economic Planning Sciences, 39(2), 125–145. https://doi.org/10.1016/j.seps.2004.03.001

Lee, D. Y., Elgowainy, A., Kotz, A., Vijayagopal, R., & Marcinkoski, J. (2018). Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. Journal of Power Sources, 393, 217–229. https://doi.org/10.1016/j.jpowsour.2018.05.012

Lim, S., & Kuby, M. (2010). Heuristic algorithms for siting alternative-fuel stations using the Flow-Refueling Location Model. European Journal of Operational Research, 204(1), 51–61. https://doi.org/10.1016/j.ejor.2009.09.032

Lin, R. H., Ye, Z. Z., & Wu, B. D. (2020). A review of hydrogen station location models. International Journal of Hydrogen Energy, 45(39), 20176–20183. https://doi.org/10.1016/j.ijhydene.2019.12.035

Liu, N., Xie, F., Lin, Z., & Jin, M. (2020). Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks. In Mitigation and Adaptation Strategies for Global Change (Vol. 25, Issue 3, pp. 477–493). Springer. https://doi.org/10.1007/s11027-019-09896-z

Miotti, M., Hofer, J., & Bauer, C. (2017). Integrated environmental and economic assessment of current and future fuel cell vehicles. International Journal of Life Cycle Assessment, 22(1), 94–110. https://doi.org/10.1007/s11367-015-0986-4

MirHassani, S. A., & Ebrazi, R. (2013). A flexible reformulation of the refueling station location problem. Transportation Science, 47(4), 617–628. https://doi.org/10.1287/trsc.1120.0430

Moriarty, P., & Honnery, D. (2019). Prospects for hydrogen as a transport fuel. International Journal of Hydrogen Energy, 44(31), 16029–16037. https://doi.org/10.1016/j.ijhydene.2019.04.278

Morrison, G., Stevens, J., & Joseck, F. (2018). Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transportation Research Part C: Emerging Technologies, 87, 183–196. https://doi.org/10.1016/j.trc.2018.01.005

New Energy Coalition. (2020). the Northern Netherlands Hydrogen Investment Plan. https://www.newenergycoalition.org/custom/uploads/2020/10/investment-plan-hydrogen-northern-netherlands-2020-min.pdf

Our World in Data. (2020). Cars, planes, trains: where do CO2 emissions from transport come from? - Our World in Data. Our World in Data. https://ourworldindata.org/co2-emissions-from-transport

Parks, G., Boyd, R., Cornish, J., & Remick, R. (2014). Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration. Related Information: Independent Review Published for the U.S. Department of Energy Hydrogen and Fuel Cells Program, May, Medium: ED; Size: 74 pp. http://www.osti.gov/scitech//servlets/purl/1130621/

PBL. (2020). Waterstof voor de gebouwde omgeving; operationalisering in de Startanalyse 2020. Pbl, 4250 (september).

PGS35. (2020). Publicatie Reeks Gevaarlijke Stoffen 35. https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS35.html

Renewable Energy Directive | Energy. (2014). https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en

Rijksoverheid. (2019). C5.7 Waterstof. 171–175. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord-hoofdstuk-waterstof

Rose, P. K., & Neumann, F. (2020). Hydrogen refueling station networks for heavy-duty vehicles in future power systems. Transportation Research Part D: Transport and Environment, 83, 102358. https://doi.org/10.1016/j.trd.2020.102358

Rose, P. K., Nugroho, R., Gnann, T., Plötz, P., Wietschel, M., & Reuter-Oppermann, M. (2020). Optimal development of alternative fuel station networks considering node capacity restrictions. Transportation Research Part D: Transport and Environment, 78, 102189. https://doi.org/10.1016/j.trd.2019.11.018

Singh, S., Jain, S., Ps, V., Tiwari, A. K., Nouni, M. R., Pandey, J. K., & Goel, S. (2015). Hydrogen: A sustainable fuel for future of the transport sector. In Renewable and Sustainable Energy Reviews (Vol. 51, pp. 623–633). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.06.040
Sloten, R. van, Fabius, B., & Aldenkamp, M. (2020). Transitiestudie verduurzaming wegtransport Transitieonderzoek verduurzaming wegtransport.
Talebian, H., Herrera, O. E., Tran, M., & Mérida, W. (2018). Electrification of road freight transport: Policy implications in British Columbia. Energy Policy, 115, 109–118. https://doi.org/10.1016/j.enpol.2018.01.004
TNO. (2013). Beladingsgraden Vrachtverkeer WiM. www.tno.nl
Upchurch, C., Kuby, M., & Lim, S. (2009). A model for location of capacitated alternative-fuel stations. Geographical Analysis, 41(1), 85–106. https://doi.org/10.1111/j.1538-4632.2009.00744.x
van der Meer, J. P., Remco, P., & de Jong, F. (2018). HyLAW - National Policy Paper - Netherlands. https://www.hylaw.eu/sites/default/files/2019-03/HyLAW_National Policy Paper_Netherlands.pdf

Appendix 5A - Mathematical model

Below, an overview of the main components of the SC-NC FRLM can be found. First the decision variables, sets & indices, and parameters will be described, after which the mathematical model in its entirety is presented.

- Decision variables:
  - z_i; binary decision variable; 1 if HRS is built at node i, 0 otherwise.
  - x_i; decision variable that indicates the amount of traffic flow in kilometres served by an opened HRS at node i. It is either equal to the flow along the HRS at node i, or it is equal to the supply capacity limit if f_i exceeds that limit, thereby complying with assumption (12).
- Sets and indices:
  - N ; set of all nodes that form the highway network
  - M ; set of OD nodes
  - k_q; set of all potential HRS nodes that are located on path q
  - Q ; set of all OD pairs
  - A_q; set of directional arcs on the shortest path q
  - i,j,k ; indices of potential facilities at nodes
  - q ; index of OD pairs
  - aj,k ; index of directional arc from node i to node j

- Parameters:
  - f_i; total volume of traffic flow along node i
  - B; fixed opening cost of building an HRS facility

- V; annual hydrogen supply cost: calculated as hydrogen cost per kg divided by p (conversion to kilometres), and multiplied by the number of days a FCET operates each year.
- S ; FCET penetration percentage (0<S<1)
- R; min. flow requirement in kg of H2 for an HRS to be opened
- C ; supply capacity limit in kg of H2
- p ; fuel efficiency; the amount of km's that can be driven on 1 kg of H2, which is important to calculate the flow in kilometres that can be covered by an HRS

The model:

$$min \sum_{i \in N} z_i B + \sum_{i \in N} x_i V \tag{1}$$

Subject to:

$$\sum_{i \in N} \frac{x_i}{p} \geq R \tag{2}$$

$$\sum_{i \in N} \frac{x_i}{p} \leq C z_i \tag{3}$$

$$\sum_{i \in N} \frac{x_i}{f_i} \geq S \tag{4}$$

$$z_i \in \{0,1\} \qquad \forall i \ \in N \tag{5}$$

$$x_i \geq 0 \qquad \forall i \ \in N \tag{6}$$

(1) the objective function seeks to minimize the sum of the total fixed opening costs of building an HRS ($\sum_{i \in N} z_i B$), and the total variable annual hydrogen supply costs ($\sum_{i \in N} x_i V$) based on the flow served along each HRS.
(2) ensures that an HRS can only be opened if at least R kilograms of H2 are demanded by the flow along an HRS. ($\frac{x_i}{p}$ is the flow served in kilograms of H2)
(3) ensures that the flow served by an HRS at node i does not exceed the supply capacity limit C in kilograms of H2. Moreover, it ensures that a flow is not possible if the corresponding facility is not decided to be opened.
(4) ensures that at least FCET penetration percentage S is fuelled.
(5) ensures that z_i can only take on binary values.
(6) ensures that x_i can only take on positive values.

Appendix 5B – Set of Highway Nodes (N)

Highway Nod	Node
1	Winschoten
2	Delfzijl
3	Groningen
4	Leeuwarden
5	Sneek
6	Drachten
7	Assen
8	Emmen
9	Meppel
10	Zwolle
11	Hoogeveen
12	Zuidbroek
13	Beilen
14	Heerenveen
15	Meendenertol
16	Roode Til
17	Veenborg
18	Dikke Linde
19	Oosterveen
20	Truck centrum Emmer
21	Groote veldblokken
22	Zwinderscheveld
23	Panjerd
24	Lageveen
25	Green Planet Pesse
26	Smalhorst
27	De mussels
28	Peelerveld
29	Zeijerveen
30	Glimmermade
31	Witte molen
32	Baarveld
33	Nijlanderveld
34	De markte
35	Haerst
36	Dekkersland
37	Paardeweide
38	Bovenboer
39	De Weeren
40	Dorpshellen
41	De Smarpot
42	Mandelan
43	Oude Riet
44	Mienscheer
45	De krellen
46	Stienkamp
47	De horne
48	Bloksloot
49	Randstad
50	Vlaanderen
51	Nordrhein
52	Niedersachsen

Appendix 5C – Set of OD nodes (M)

ORIGIN/DESTINATION	NUTS3 code
Winschoten	NL111
Delfzijl	NL112
Groningen	NL113
Leeuwarden	NL124
Sneek	NL125
Drachten	NL126
Assen	NL131
Emmen	NL132
Meppel	NL133
Zwolle	NL211
Randstad	NLR
Vlaanderen	BE
Nordrhein	DENO
Niedersachsen	DENI

Appendix 5D – Set of potential HRS nodes

node id (z_i)	Location name	Highway
15	Meendenertol	A7H
16	Roode Til	A7T
17	Veenborg	A7T
18	Dikke Linde	A7H
19	Oosterveen	A37H
20	Truck centrum Emmen	A37T
23	Panjerd	A28T
25	Green Planet Pesse	A28H
26	Smalhorst	A28H
29	Zeijerveen	A28T
30	Glimmermade	A28H
32	Baarveld	N33H
33	Nijlanderveld	N33T
35	Haerst	A28T
36	Dekkersland	A28H
37	Paardeweide	A32T
38	Bovenboer	A32H
39	De Weeren	A32T
42	Mandelan	A32T
43	Oude Riet	A7T
44	Mienscheer	A7H
45	De krellen	N31T
46	Stienkamp	N31H
47	De horne	A7H
48	Bloksloot	A7T

Appendix 5E – Set of Directional Arcs

Set of directional arcs

directional arcs	directi	highwa	begin	end	arc path (a	ArcL
1	A7H	A7	Sneek	De Horne	a_5,47	18
2	A7T	A7	Bloksloot	Sneek	a_48,5	8
3	A7H	A7	De Horne	Heerenveen	a_47,14	7
4	A7T	A7	Heerenveen	Bloksloot	a_14,48	18
5	A7H	A7	Heerenveen	Drachten	a_14,6	23
6	A7T	A7	Drachten	Heerenveen	a_6,14	22
7	A7H	A7	Drachten	Mienscheer	a_6,44	17
8	A7T	A7	Oude Riet	Drachten	a_43,6	20
9	A7H	A7	Mienscheer	Groningen	a_44,3	22
10	A7T	A7	Groningen	Oude Riet	a_3,43	20
11	A7H	A7	Groningen	Dikke Linde	a_3,18	11
12	A7T	A7	Veenborg	Groningen	a_17,3	13
13	A7H	A7	Dikke Linde	Zuidbroek	a_18,12	12
14	A7T	A7	Zuidbroek	Veenborg	a_12,17	11
15	A7H	A7	Zuidbroek	Meendenert	a_12,15	5
16	A7T	A7	Roode Til	Zuidbroek	a_16,12	5
17	A7H	A7	Meendenert	Winschoten	a_15,1	10
18	A7T	A7	Winschoten	Roode Til	a_1,16	10
19	A28H	A28	Zwolle	De Markte	a_10,34	9
20	A28T	A28	Haerst	Zwolle	a_35,10	8
21	A28H	A28	De Markte	Dekkersland	a_34,36	8
22	A28H	A28	Dekkersland	Meppel	a_35,9	10
23	A28T	A28	Meppel	Haerst	a_9,35	19
24	A28H	A28	Meppel	Lageveen	a_9,24	12
25	A28T	A28	Panjerd	Meppel	a_23,9	13
26	A28H	A28	Lageveen	Hoogeveen	a_24,11	12
27	A28T	A28T	Hoogeveen	Panjerd	a_11,23	11
28	A28H	A28	Hoogeveen	Green Planet	a_11,25	9
29	A28T	A28	Green Planet	Hoogeveen	a_25,11	8
30	A28H	A28	Green Planet	Smalhorst	a_25,26	9
31	A28T	A28	De Mussels	Green Planet	a_27,25	8
32	A28H	A28	Smalhorst	Beilen	a_26,13	5
33	A28T	A28	Beilen	De Mussels	a_13,27	5
34	A28H	A28	Beilen	Assen	a_13,7	14
35	A28T	A28	Assen	Beilen	a_7,13	15
36	A28H	A28	Assen	Peelerveld	a_7,28	7
37	A28T	A28	Zeijerveen	Assen	a_29,7	6
38	A28H	A28	Peelerveld	Glimmermad	a_28,30	14
39	A28T	A28	Witte Molen	Zeijerveen	a_31,29	16
40	A28H	A28	Glimmermad	Groningen	a_30,3	10
41	A28T	A28	Groningen	Witte Molen	a_3,31	9
42	A32H	A32	Leeuwarden	De Smarpot	a_4,41	25
43	A32T	A32	Mandelan	Leeuwarden	a_42,4	14
44	A32H	A32	De Smarpot	Heerenveen	a_41,14	9
45	A32T	A32	Heerenveen	Mandelan	a_14,42	22
46	A32H	A32	Heerenveen	Dorsphellen	a_14,40	7
47	A32T	A32	Paardeweide	Heerenveen	a_37,14	34
48	A32H	A32	Dorpshellen	Bovenboer	a_40,38	25
49	A32H	A32	Bovenboer	Meppel	a_38,9	7
50	A32T	A32	Meppel	Paardeweide	a_9,37	9
51	A37H	A37	Hoogeveen	Groote veldt	a_11,21	12
52	A37T	A37	Zwindersche	Hoogeveen	a_22,11	12
53	A37H	A37	Groote veldt	Oosterveen	a_21,19	25
54	A37T	A37	Truck Centru	Zwindersche	a_20,22	24
55	A37H	A37	Oosterveen	Emmen	a_19,8	16
56	A37T	A37	Emmen	Truck Centru	a_8,20	7
57	N31H	N31	Leeuwarden	Stienkamp	a_4,46	22
58	N31T	N31	De Krellen	Leeuwarden	a_45,4	28
59	N31H	N31	Stienkamp	Drachten	a_46,6	7
60	N31T	N31	Drachten	De Krellen	a_6,45	8
61	N33H	N33	Assen	Baarveld	a_7,32	9
62	N33T	N33	Nijlanderveld	Assen	a_33,7	8
63	N33H	N33	Baarveld	Zuidbroek	a_32,12	36
64	N33T	N33	Zuidbroek	Nijlanderveld	a_12,33	35
65	N33H	N33	Zuidbroek	Delfzijl	a_12,2	26
66	N33T	N33	Delfzijl	Zuidbroek	a_2,12	25
67	N381H	N381	Drachten	Beilen	a_6,13	43
68	N381T	N381	Beilen	Drachten	a_13,6	43
69	N381H	N381	Beilen	Emmen	a_13,8	30
70	N381T	N381	Emmen	Beilen	a_8,13	31
71			Randstad	Heerenveen		141
72			Vlaanderen	Heerenveen		297
73			Nordrhein	Zwolle		195
74			Niedersachs	Winschoten		212