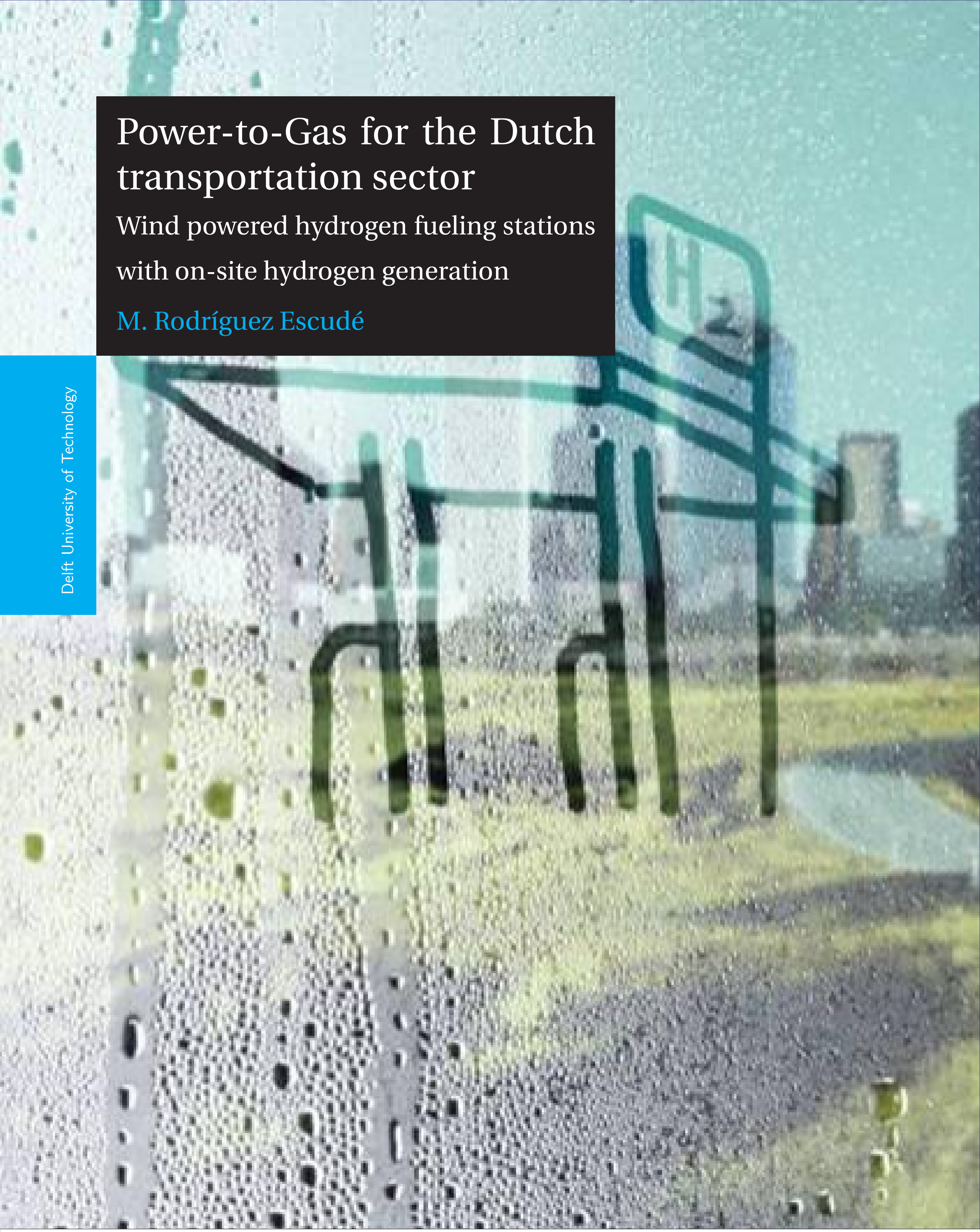

Power-to-Gas for the Dutch transportation sector

Wind powered hydrogen fueling stations with on-site hydrogen generation

M. Rodríguez Escudé

Delft University of Technology

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Challenge the future

Power-to-Gas for the Dutch transportation sector

Wind powered hydrogen fueling stations with on-site hydrogen generation

by

M. Rodríguez Escudé

in partial fulfillment of the requirements for the degree of

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Abstract

The focus of this investigation is the location, sizing and performance of a Hydrogen Fueling Station (HFS) in The Netherlands in 2030. The transportation sector is one of the main air pollution sources, reaching 17% of the total emissions from The Netherlands in 2015. By promoting zero emission vehicles, like Fuel Cell Electric Vehicles (FCEVs), The Netherlands could reduce its environmental impact and reach its future emission goals.

The proposed HFS model consists of a wind turbine, electrolyzer, hydrogen compression and storage system, hydrogen cooling and dispensing system, and a hydrogen tube trailer for buying or selling hydrogen on the industrial market. This system is capable of producing hydrogen on-site with wind energy, reducing the emissions from hydrogen production. The location was based on the re-utilization of existing petrol fueling stations in The Netherlands, meaning that around 3,800 locations were considered. Based on existing legislation for wind turbine placement that regulate noise, safety, and environmental protection, locations were filtered to eliminate infeasible petrol fueling stations, thus leaving 106 locations that allow to install a wind turbine (2.7 % of the existing petrol fueling stations).

By extrapolating the possible hydrogen demand from a single HFS, an hourly demand profile for a whole year was created. The annual consumption was based on the expected petrol dispensed by an average Dutch petrol fueling station in 2030. This demand profile considered hourly, weekly, and seasonal variations in demand.

The GIS study indicated that Zoetermeer had average conditions from the feasible locations. Therefore, the wind speed profile was taken from a nearby weather station in Voorschoten. Surface roughness was studied to perform the wind speed extrapolation from 10 m to 160 m, the hub height of the wind turbine.

To select the sizes of the wind turbine, electrolyzer, and grid capacity, 90 HFS configurations were simulated and compared with minimum values of environmental ($kgCO_2eq/kgH_2$), reliability (Loss of Supply Probability and Equivalent Loss Factor), and financial metrics (CAPEX, OPEX, and LCoH). The recommended system configuration was: one 4.2 MW wind turbine, a PEM electrolyzer with a capacity of 45 kgH_2/hour (2.4 MW), and 1 MW grid connection for the electrolyzer. The HFS is capable of producing 335 tH_2 per year, at € 5.034 /kgH_2 with 2.74 $kgCO_2eq/kgH_2$. This configuration requires a CAPEX of €13.2 M and an annual OPEX of € 1.39 M. The efficiency of the complete HFS is 56.4 kWh/kgH_2.

If implemented in all the feasible locations, the proposed HFS has the capacity to supply hydrogen to 289,000 passenger FCEVs, removing 467 $ktCO_2eq$ from the environment every year. Although this is only 1.4% of the total transportation emissions, it is a step in the right direction to reduce the CO_2 emissions in The Netherlands.

Acknowledgements

"Is this the summit, crowning the day? How cool and quiet! We're not exultant; but delighted, joyful; soberly astonished. . . Have we vanquished an enemy? None but ourselves. Have we gained success? That word means nothing here. Have we won a kingdom? No. . . and yes. We have achieved an ultimate satisfaction. . . fulfilled a destiny. . . To struggle and to understand - never this last without the other; such is the law. . ."

George Mallory

This has been a long and interesting journey that led me to academic, professional, and personal development beyond my expectations. This was only possible with the support from my family. Being away from home becomes easier when you have that sorted out.

Special thanks to my daily supervisor, Nikos, that helped me a lot throughout the whole thesis process. We had countless meetings and brainstorming sessions that were key to complete all the objectives. Also, to my main supervisor, Prof. dr. Ad van Wijk, for helping me shape the thesis into a concrete project, supported by all his experience.

Finally, to all my friends here in Delft, and back in Costa Rica. For their support, jokes, and constant "When are you going to finish your thesis?" comments. It would be impossible for me to name everyone. Special mention to all the ticos and the FvB 6I group, you know who you are.

M. Rodríguez Escudé
Delft, June 2019

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List of Abbreviations

AWE	Alkaline Water Electrolysis
BEV	Battery Electric Vehicles
CAPEX	Capital Expenditure
CF	Capacity Factor
CRF	Capital Recovery Factor
C&S	Compression and Storage
ELF	Equivalent Loss Factor
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FFS	Feasible Fueling Station
FS	Fueling Station
GIS	Geographic Information Systems
GPS	Global Positioning System
HFS	Hydrogen Fueling Station
ICE	Internal Combustion Engine
LCoE	Levelized Cost of Energy
LCoH	Levelized Cost of Hydrogen
LoSP	Loss of Supply Probability
LPG	Liquefied Petroleum Gas
NREL	National Renewable Energy Laboratory
OPEX	Operational Expediture
PEM	Proton Exchange Membrane
PM	Particulate Matter
POI	Point of Interest
SMR	Steam Methane Reforming

1

INTRODUCTION

The economy of The Netherlands is heavily dependent on natural gas reserves to maintain its economy and energy demand for electricity and heating [1]. Given the current objectives to reduce CO_2 emissions according to the Paris Agreement [2, 3], new solutions need to be implemented to support the transition to cleaner energy sources in the electricity, transportation, and heating sectors [4].

Considering the extensive natural gas infrastructure already in place, the experience handling natural gas since the 1960's [5], and the energy savings from distributing energy using pipelines [1], using hydrogen to re-purpose the gas infrastructure is within the main possibilities for the dutch energy transition process. Additionally, The Netherlands has great offshore and onshore wind energy potential that can be used to produce electricity with one of the lowest CO_2 per kWh of all the renewable energy sources [6, 7].

With the above considerations in mind, large scale hydrogen generation and distribution can have a major positive impact to the electricity, heating, transportation, and chemical sectors. Electricity and heat can be produced with fuel cells systems or hydrogen oxygen steam generators to reuse current natural gas power plants. The transportation sector is already commercializing or experimenting with cars, buses, forklifts, trucks, trains, motorcycles, and bicycles powered by fuel cells, aiming to reduce pollution and increase the efficiency of vehicle's power trains. Hydrogen and oxygen are an important feedstock to the chemical sector, which could also benefit from lower costs and CO_2 footprint.

The main problem with the proposed hydrogen economy is that, currently, around 95% of the world's hydrogen is produced using fossil fuels [8]. These methods produce carbon monoxide and carbon dioxide as by-products. To support a clean transition, hydrogen should be produced by electrolysis using electricity from renewable sources. As the transportation sector is responsible for almost 20% of greenhouse emissions in The Netherlands [9], this could be the first step to start the transition.

Offshore wind farms planned for the north sea has a great potential hydrogen production, coupling hydrogen production with storage in salt caverns located in Groningen. Transporting hydrogen through the transmission and distribution gas systems is being considered, as hydrogen is an appealing energy carrier for multiple industries. Large scale hydrogen storage is suitable to counteract the seasonal fluctuations of wind energy and provide a stable energy distribution. The feasibility of these proposals is under analysis by the Energy Research Centre of the Netherlands (ECN), DNV GL, Top Consortium for Knowledge and Innovation (TKI in Dutch), Akzonobel, and other key stakeholders in the electricity and gas markets [10, 11].

Supporting these centralized proposals in the transition of the energy sector, decentralized solutions could support the introduction of hydrogen in specific locations. On-site hydrogen production powered by wind energy could cover part of the demand in the initial steps of the roll-out of Fuel Cell Electric Vehicles (FCEVs). This study focuses on this section of the energy transition, resulting in a system proposal for localized hydrogen production. These systems can be coupled to the large-scale hydrogen energy vision for The Netherlands [1, 11, 12].

The proposal detailed in this document considers wind energy as an energy source to generate hydrogen via electrolysis in the locations of existing fuelling stations in The Netherlands. The idea behind this approach is to re-utilize part of the existing fueling station infrastructure and take advantage of their strategic placement for hydrogen distribution. The produced hydrogen would be used to satisfy the demand of a Hydrogen Fueling Station (HFS) according to the 2030 expectation for the hydrogen economy [1, 12]. The main focus of the investigation is to understand the impact of the backup grid connection of the hydrogen generation system on the final hydrogen price to the consumer, as well as the system reliability and linked CO_2 emissions. The aim was to find a system configuration that supplies the hydrogen demand, balancing the dependence on grid electricity and gray hydrogen purchased by fossil fuels.

The motivation for this investigation is the need to understand how different design, sizing, and operation strategies impact the technical and economical performance of a HFS. As every country has different energy sources and demand profiles according to their own characteristics, each of them should be studied individually to adjust the HFS performance to real requirements. Therefore, this study aims to give extra perspective on how HFSs should be configured and sized for the future hydrogen demand for transportation in The Netherlands.

1.1. VISION FOR A CLEANER DUTCH TRANSPORTATION SECTOR

According to the Energy Agenda [13], published by the Ministry of Economic Affairs, The Netherlands will focus mostly on the reduction of CO_2 emissions instead of increasing its share of renewables, due to the high cost of those goals. Electricity generation from wind and solar photovoltaic systems is expected to grow from private investments, therefore helping to de-carbonize the energy sector. Greenhouse gas emissions in The Netherlands in 2015, shown in Figure 1.1, totalled 196 CO_2 Mt equivalent, from which 17% were produced by the transportation sector [13].

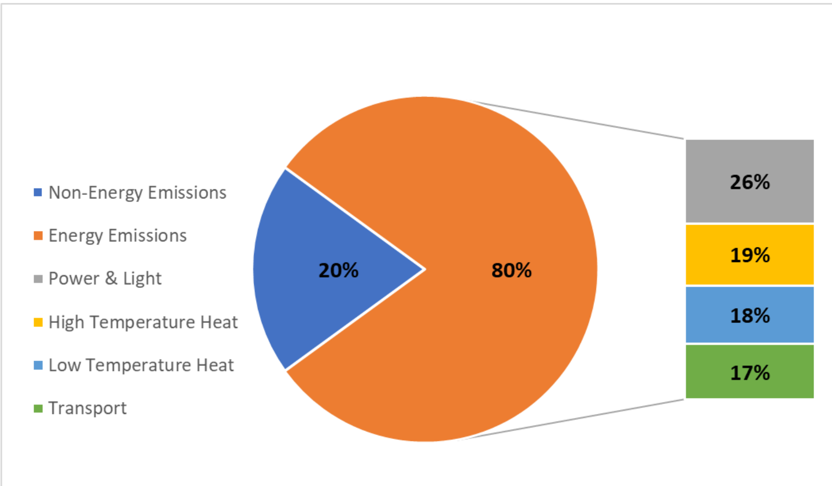


Figure 1.1: Greenhouse gas emissions in The Netherlands, per sector, in 2015.

Zero emission transportation, as stated in "A vision of sustainable fuels for transport" [12], can be achieved with clean electric transportation, green hydrogen, biofuels, and renewable gas. To help reduce pollution in urban areas, passenger vehicles and scooters are the focus of this investigation. Passenger cars are one of the main CO_2, ozone, fine dust, and NO_X emitters, while scooters pollute the environment with gases and fine dust particles ($PM_{2.5}$). If heavy duty vehicles are included in the technological transition, the positive impact on emissions would be greater [14]. Even if the electricity used for electrolysis comes from a fossil fuel intensive electric grid, emissions are reduced due to the higher efficiency of fuel cells [15]. Switching to fuel cell vehicles could lead to a reduction of 90% in CO_2 equivalent green house emissions if hydrogen is produced from wind energy with electrolysis, comparing the well-to-wheel emissions per driven kilometer to gasoline vehicles [16].

The Netherlands has been investing in electric car infrastructure with public charging stations and incentives for electric vehicles [17]. The introduction of a higher amount of electric vehicles has caused a reduction between 13-6% in CO_2 emission per kilometer, although the fossil fuel intensive electricity grid in The Netherlands reduces the positive environmental impact of these technologies [18]. In the future, the vehicular fleet will be a mixture of Battery Electric Vehicles (BEV) and FCEVs. Different requirements of range, driving cycles, cargo capacity and so on will define if users opt for a battery or fuel cell drivetrain. For heavy load transportation, such as freight trucks, a battery in the MWh range would be necessary to reach a similar range as diesel trucks. Batteries with current technology with such energy capacity weigh several tonnes, limiting the cargo capacity of the truck and reducing the feasibility of a BEV truck for long distances. This indicates that BEVs and FCEVs will adjust to the needs of different users, both providing zero emission transportation.

Currently, multiple FCEVs are being developed and commercialized, with opportunities to power auxiliary power units, light and heavy duty vehicles, and cargo ships [19]. Companies like Toyota, Hyundai, and Honda already have FCEVs in the market, with distribution limited to locations with sufficient amount of HFS. The state of California in The United States is acting as a proving ground for these vehicles due to the high concentration in Los Angeles and San Francisco. Nikola Motors developed a fuel cell powered heavy truck and its planning to develop 330 HFSs across the interstate highway system in The United States, and a total of 700 by 2028 [20]. Japan is also pushing this technology, from passenger cars to mass transit like buses, to the point that the 2020 Olympics will showcase a hydrogen powered olympic village, with fuel cell buses for transportation [21]. The train company Alstom deployed and successfully tested its Coradia i-Lint fuel cell passenger train. The train, operating in Germany, is capable of 800 km between refills. The long range eliminates the need for overhead electric cabling, this reducing initial investment and maintenance costs. Scandinavian countries are currently working to complete a hydrogen highway, with Denmark reaching 50% of the population within 15 km to a Hydrogen Fueling Station (HFS). All these countries are acting as accelerators of research and scalability to reduce hydrogen prices and improve generation and dispensing efficiency, making these technologies available for other countries at a more affordable cost.

As mentioned in The Green Hydrogen Economy in the Northern Netherlands [1], and The Energy Agenda of The Netherlands [13], the fossil fuel dependent transportation sector provides a great opportunity to reduce CO_2 emissions using green hydrogen. There are multiple hydrogen production plants already operational in the country, including privately owned hydrogen pipelines to feed the chemical industry, but most of the hydrogen is produced with natural gas. Steam methane reforming and water-gas shift reactions, the most common used processes in the industry for hydrogen production, have high quantities of carbon dioxide and carbon monoxide as by-products [22].

Hydrogen needs to be produced with Renewable Energy Sources (RES) to de-carbonize the transportation sector, meaning blue or green hydrogen production. There are multiple methods to do this, but electrolysis is a mature technology that only generates hydrogen and oxygen by splitting water using electricity, and if the electricity is produced with RESs, the entire process would be greenhouse emission free. Electricity sources like geothermal, wind, solar, biomass, and even nuclear energy can be considered for this purpose, although nuclear electricity has additional environmental and safety concerns [8, 23, 24]. Wind energy is a recommended RES for green hydrogen production in The Netherlands because of high wind speeds, experience with wind technology, and availability of offshore wind sites.

To summarize, The Netherlands needs to reduce the emissions from the transportation sector and its dependence on fossil fuels. Although a high percentage of transportation is done with electric trains, most passenger vehicles use petrol or diesel [25]. Providing the population with green hydrogen to use it on FCEVs would heavily reduce the transport sector emissions. Therefore, identifying the most suitable locations for green hydrogen production from wind energy, and modelling how HFSs behave with the expected future hydrogen demand will help to tackle the technical difficulties of reducing the emissions of the Dutch transportation sector.

1.2. PROPOSAL

This investigation focuses on the simulation of a HFS with wind powered electrolysis in The Netherlands, in the year 2030. As of 2017, there were only around 6,000 FCEVs driving on the roads worldwide, mainly distributed in United States (53%), Japan (38%), and Europe (9%) [26]. Because of the low amount of vehicles, the utilization factor (ratio between the dispensed hydrogen and the capacity of the HFS) of the HFSs in United States had an average of 20% in 2017. Therefore, the proposal was set to the year **2030** to simulate a HFS working at full capacity in the future, with more FCEVs in the market.

The main assumption for the dimensioning of such HFS is that it shall have the capability to service an equivalent amount of vehicles as a standard Dutch petrol station. The vehicle fleet growth and the increase in daily travelled distance was considered to adjust the current fueling station sizes to 2030 expectations. The conversion from dispensed petrol to dispensed hydrogen was based on the travelled distance, considering the expected efficiency of FCEVs in 2030. This assumes the same driving behaviour for the users of the FCEVs and Internal Combustion Engine (ICE) passenger vehicles, as compared by the National Renewable Energy Laboratory (NREL) of the USA in California [27].

An hourly demand profile was created considering daily, weekly, and seasonal variations in demand while maintaining the yearly average. However, this data was based on the consumption patterns from United States due to the lack of detailed European data. Another important input for the model was the hourly wind speed profile. A Geographic Information System (GIS) study was performed to define the feasible locations to install a wind turbine in The Netherlands. National legislation was reviewed to define the areas where wind turbines are prohibited, considering safety and noise in urban areas, areas protected by environmental legislation, airports, and others. In order to re-purpose the existing fueling stations, which are located near zones with high vehicular flow, their locations were used as the possible locations for the installation of a wind turbine system. This allows understanding the countrywide potential for HFSs with on-site generation powered by wind turbines. From these feasible locations, representative location was selected based on its proximity to densely populated areas, highways, and wind class. A local surface roughness analysis was performed in the selected location to have a representative and realistic wind speed profile as an input for the model.

The simulation model was set up using the components shown in Figure 1.2. The wind speed profile was used as an input for the wind turbine system. Additional grid capacity was considered as a backup electricity source for the electrolyzer. The wind turbine, the grid connection, and the electrolyzer are the components for hydrogen production. For Compression and Storage (C&S), the low pressure compressor takes hydrogen from the electrolyzer and stores it in the main tank at medium pressure (200 bar). A tube trailer was considered for the transportation section of the system, to buy or sell hydrogen according to the balance between

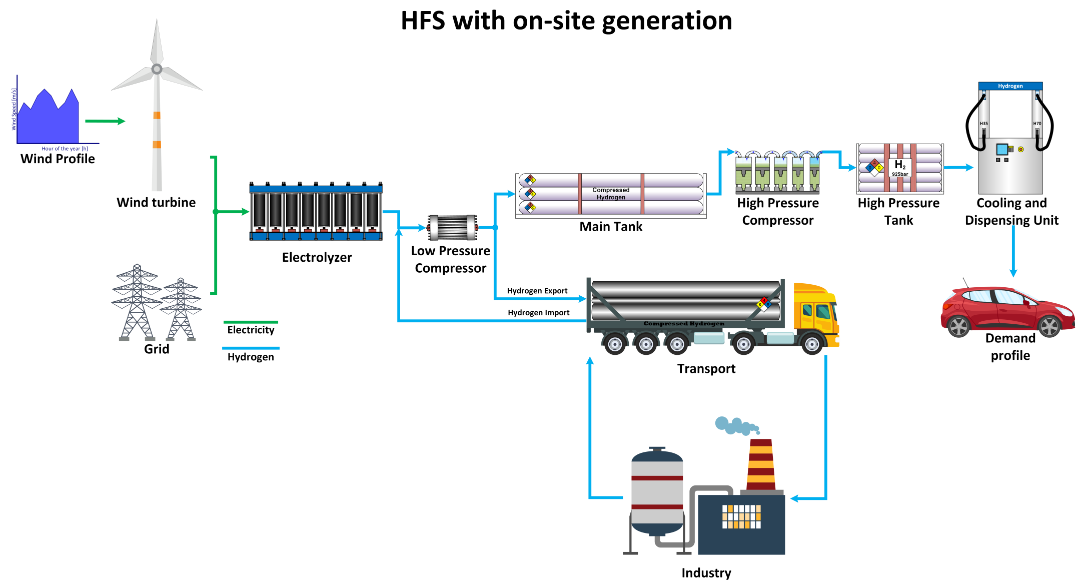


Figure 1.2: Diagram of a wind powered hydrogen fuelling station with on-site generation.

production and demand. Large scale hydrogen suppliers or consumers were assumed to provide or purchase the hydrogen production mismatch. Finally, the high pressure compressor (700 bar), cooling system, and the dispenser complete the dispensing section of the system.

The model allows to compare the size of the main components: wind turbine capacity by the rated power, grid connection capacity, and electrolyzer capacity. The variations of the component sizes were selected based on the hydrogen demand, allowing to compare under and over sized systems with reliability, economic, and environmental metrics. All the different component sizes resulted in 90 different HFS configurations. The objective of this comparison was to select one of the systems as the recommended for implementation based on the simulation results. This system was later analysed for its technical and economical feasibility to show which design aspects were beneficial or detrimental to the performance of the HFS. The component cost breakdown analysis and the components of the final price of hydrogen were analysed with the selected system configuration. Finally, the impact of the selected HFS configuration at a national level was assessed, based on the previous GIS analysis.

1.3. RESEARCH QUESTIONS

The hypothesis of this investigation was that a wind powered HFS with backup grid connection and on-site generation has a lower price of hydrogen (€/kg H_2) and higher reliability than a similar HFS without backup grid connection. In order to corroborate this hypothesis with the model proposed in section 1.2, the following research questions were considered:

- How many existing fueling stations in The Netherlands can be converted to HFSs, powered by wind energy?
  - What are the zoning restrictions for wind turbine installations?
  - What is the distribution of these stations across The Netherlands, and their relation to population and vehicle quantity?
  - Which of the feasible locations is most representative for The Netherlands to develop the proposed HFS?

- What is the expected hydrogen demand profile of a HFS in The Netherlands in 2030?
  - What is the current fuel consumption profile for gasoline fueling stations?
  - How does the fuel consumption pattern change during the day, week or different seasons?
- Which is the optimal system configuration for a HFS with wind powered on-site hydrogen generation?
  - Which HFS configuration is the most suited for implementation, based on the proposed metrics?
  - What is the effect of grid connection as backup for the hydrogen generation system on the autonomy of the HFS?
- What is the cost distribution of a HFS optimized for the Dutch demand in 2030?
  - What is the impact of each component on the price of the HFS?
  - What is the cost distribution for hydrogen production, compression and storage, transportation, and distribution?
  - How does buying or selling hydrogen affect the price of hydrogen to the consumer?
- What share of the demand of personal vehicles could be covered by the proposed HFS configuration if applied at a national scale in The Netherlands in 2030?

1.4. DOCUMENT STRUCTURE

The research follows a top-down approach, gathering all the information needed from a national scale, down to a system level. This allowed to quantify the potential of this proposal in terms of scalability, while also considering the behaviour of a single system. In Chapter 2, a country-wide study using GIS was performed to select all the feasible petrol fueling stations for wind turbine placement, based on zoning and nature protection regulations. This section allowed to select a representative location of The Netherlands to model the HFS with real wind speed data and terrain characteristics.

Chapter 3 explains the proposed model, with all the components, logic, and the customized inputs from The Netherlands: the wind availability and expected hydrogen demand for 2030. This chapter also includes the details about the metrics to evaluate the performance of all the proposed system configurations.

The results from the evaluation of the different HFS configurations are presented and analysed in Chapter 4. Based on these results, a recommended system was selected and analysed in depth in Chapter 5 in terms of performance, sustainability and economics, including the possible impact of its implementation at a national scale. Finally, Chapter 6 summarizes the conclusions and recommendations based on the findings of this investigation.

2

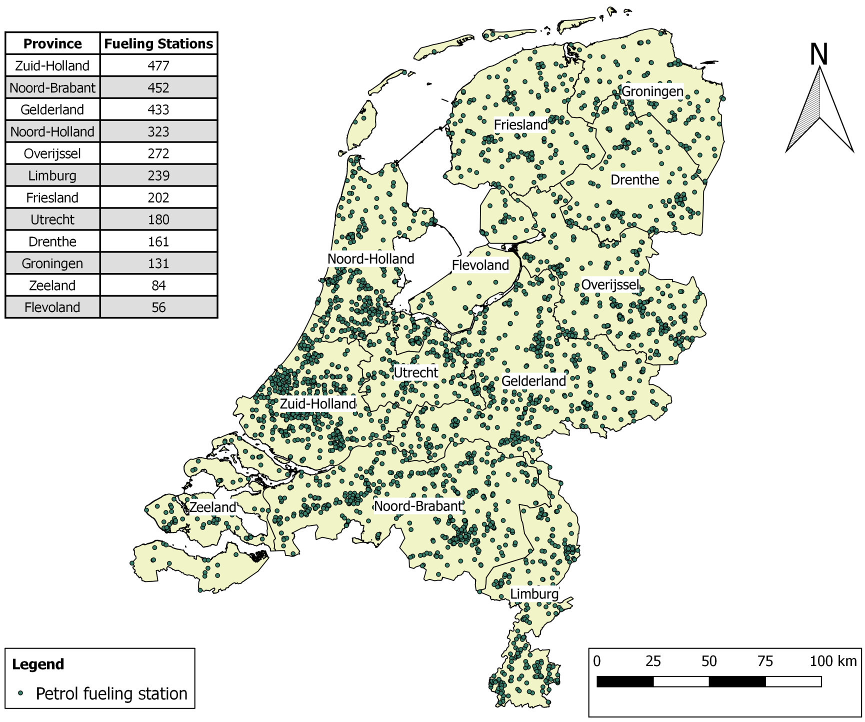
Feasible locations for wind turbine installation

Which Dutch petrol stations can have a wind turbine installed at their location?

A GIS study was performed to understand the potential to install wind turbines in The Netherlands in the vicinity of existing petrol fueling stations. The current distribution of petrol fueling stations is shown in Figure 2.1. The objective of this study was to eliminate all the locations where, because of Dutch legislation regarding health, safety, and environment, it is not allowed to install wind turbines. These zones are referred to as buffer zones within the document. These locations allowed to estimate the potential of the proposed HFS if implemented at a national scale, based on the wind availability.

The filtering process of existing petrol stations was based on the proximity to existing wind turbines, residential and commercial areas, airports, and environmentally protected sites. Dutch laws and regulations define the safety distance to install wind turbines, mainly considering noise pollution, interference with airport operation, and protection of areas were nature could be endangered by the operation of the wind turbine. These regulations limited the feasible petrol stations for wind turbine installation to 2.7% of all locations. The proximity of most fueling stations to residential areas is the main factor for such reduction.

Information about the legislation and regulations used in this study is presented in Annex A. Additional information about the GIS datasets can be found in Table B.1.



Province	Fueling Stations
Zuid-Holland	477
Noord-Brabant	452
Gelderland	433
Noord-Holland	323
Overijssel	272
Limburg	239
Friesland	202
Utrecht	180
Drenthe	161
Groningen	131
Zeeland	84
Flevoland	56

Figure 2.1: Existing fueling stations per province in The Netherlands, according to the 2017 OSM dataset.

2.1. METHODOLOGY TO ELIMINATE INFEASIBLE LOCATIONS

This section describes the methodology followed to filter the existing petrol fueling stations, in order to eliminate the ones inside in the buffer zones where wind turbine installation is prohibited by Dutch laws or regulations. The methodology is shown in Figure 2.2, including the buffer zones used.

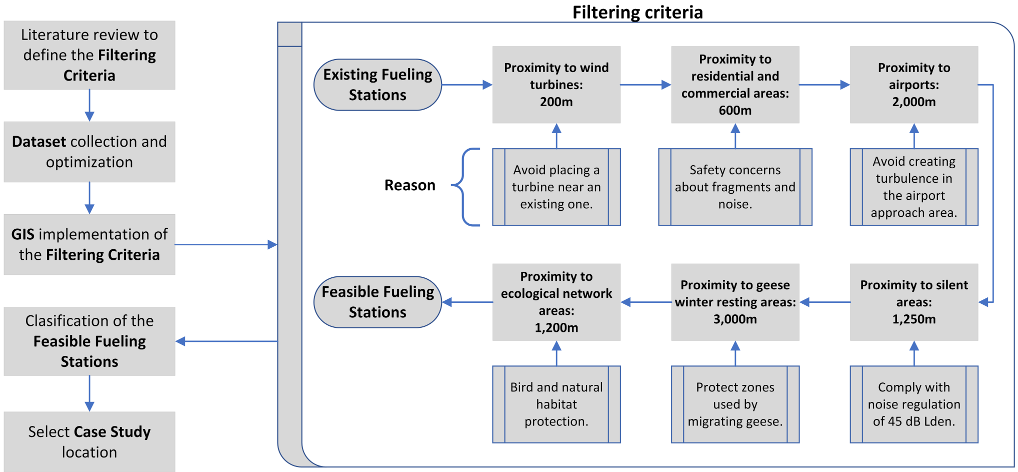


Figure 2.2: Filtering methodology for petrol fueling stations.

Initially, literature and legislation was reviewed to define the filtering criteria. With this, relevant datasets were identified, leading to optimize the data to implement the GIS study. The main regulations considered were the Spatial Planning Act (Wet Ruimtelijke Ordening), Handbook of risk zones for wind turbines (Handboek Risicozonering Windturbines), and ecological and natural protection law (Natuurbeschermingswet). The buffer zones were set based on the indications and recommendations of these documents. The details of these regulations are presented in Annex A.

After the filtering process, the resulting locations were considered as feasible petrol fueling stations to install wind turbines. These were classified according to the wind potential in their specific location. Also, the quantity of feasible locations in each province is presented to have a notion of the distribution regarding population density and vehicular fleet. Finally, a specific location was selected based on proximity to high population density areas, feasible fueling stations in the surrounding areas, and wind availability.

2.2. FILTERING OF EXISTING PETROL FUELING STATIONS BY ZONING REGULATIONS

From the gathered data sets, the locations of existing petrol fueling stations were not completely up to date. Because of this, two different location datasets were filtered, merged, and finally duplicated locations were eliminated. Additional reviews of the locations were done using Google Maps and the websites of the operating companies to assure that the used information was accurate. The difference in the number of fueling stations of the datasets is because the dependence on user inputs and updates, so using 2 different datasets includes more locations that may be missing from a single dataset.

As a starting point, the fueling stations data set from the GPS POI website had duplicated locations, with the same fueling station having 2 data points, one for the petrol pumps and another one for the Liquefied Petroleum Gas (LPG) pumps. To eliminate these duplicated locations, a filter of 50 m around the fueling stations was used. This removed the duplicated locations with the LPG classification, reducing the data set from 4,899 locations to 3,895 in the GPS-POI dataset. The petrol fueling stations dataset from OSM contained 3,021 locations and was used with the original data.

The filtering methodology resulted in 106 feasible fueling stations after merging both filtered data sets. Approximately 97% of the fueling stations were removed, mainly due to the proximity to residential and commercial zones.

2.2.1. PROXIMITY TO EXISTING WIND TURBINES

Considering that The Netherlands has a high number of wind turbines installed all over the country, with more installed in Flevoland (564), Friesland (324), and North-Holland (299), the existing fueling stations from both data sets were filtered using a 200 m radius from every existing wind turbine. This means a separation distance of more than three times the diameter of the average wind turbine installed in The Netherlands, at around 60 m [28]. This was done to avoid turbulence and interference between the existing turbines and the possible locations of the proposed HFSs. Figure 2.3 shows 2 of the removed fueling stations in the Heerhugowaard municipality, as they are within 200 m of an existing wind turbine. The reduction caused by this filtering step had a small effect on the number of feasible fueling stations, as the reduction was on average 0.4% of for both petrol station location datasets.

Existing wind turbines open the possibility to connect to the HFS and reduce the initial investment costs, as the wind turbine is already in place. Another possibility is to have the HFS completely grid connected and buy the electricity from these nearby projects. However, the possible market for hydrogen in the area should be studied beforehand, besides the technical benefits from the location.

2.2.2. PROXIMITY TO RESIDENTIAL, COMMERCIAL, AND RETAIL AREAS

For residential, commercial, and retail areas, the zoning classification from Open Street Maps was used because it was more updated than other datasets available from 2012, like the Corine Land Cover. According to Table 4 in the Handbook for Risk Zones for Wind Turbines [29], the recommended distance between wind tur-

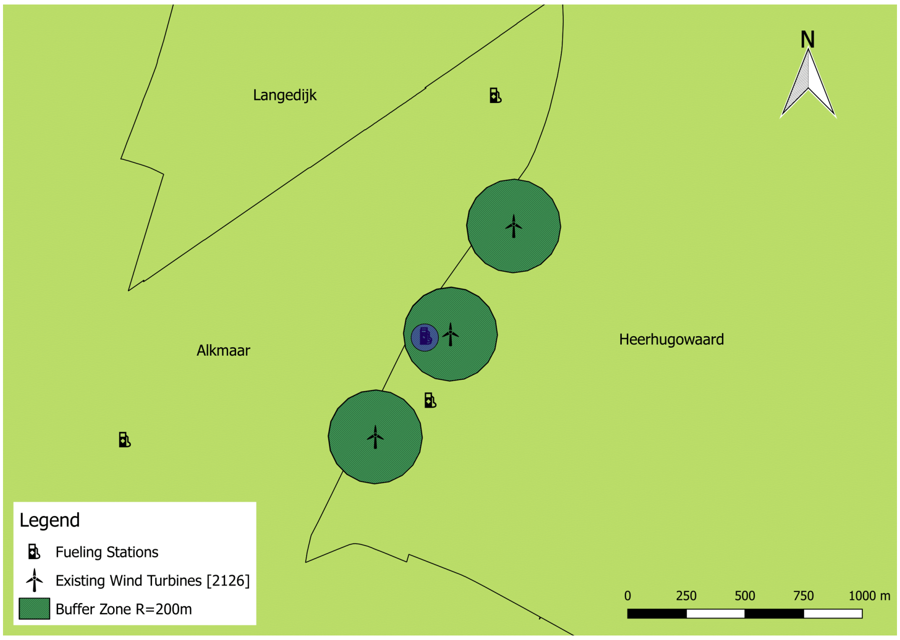


Figure 2.3: Filtering of fueling stations by a filter of 200 m proximity radius to wind turbines. Removed fueling stations (purple) in Heerhugowaard municipality.

bines and residential buildings can be: the tower height plus blade length, or the maximum throw distance. The maximum throw distance depends on the tip speed and length of the blade, and defines the distance that a blade fragment or ice piece can travel if detached from the tip of the blade while moving at rated tip speed. Considering a 5 MW wind turbine, the maximum throw distance was estimated to 600 m under nominal operating conditions, based on the simulations by Sarlak and Sørensen [30].

The 600 m buffer distance caused a mayor reduction in the amount of feasible locations, being responsible for 91% of the removed fueling stations for both data sets, as shown in Table 2.1. Figure 2.4 shows 24 fueling stations in the Delft and Pijnaker-Nootdorp area. From these, 21 were eliminated from the feasible fueling station list.

2.2.3. PROXIMITY TO AIRPORTS

Regarding airport zones, a setback distance of 2,000 m was selected due to the turbulence caused by wind turbines, as well as obstacle regulations in the approach areas [31]. Figure 2.5 shows the area of Schiphol airport, the 2,000 m setback distance, and the fueling stations inside said area (marked with purple). In Table 2.1 can be seen that the reduction caused by this filter was around 0.3% of the removed fueling stations. For the selected case of Schiphol airport it is important to note that the previous filter of residential and commercial areas (section 2.2.2) had already removed 12 of the 15 fueling stations within the 2,000 m airport filter. This case is similar for other airports that have commercial areas nearby.

2.2.4. PROXIMITY TO ENVIRONMENTALLY PROTECTED SITES

For the protected sites, three classifications were considered: silent zones, geese winter resting areas, and the ecological network. Designated silent zones require noise levels below 47 dB L_{den} (day, evening, night logarithmic average noise level) for leisure activities for the population. As a reference, a constant 40 dB noise level for 24 hours a day converts to 46.7 dB L_{den} [32]. The ecological network was considered for nature protection zones, mostly focused on bird habitats. Geese winter resting areas were considered because

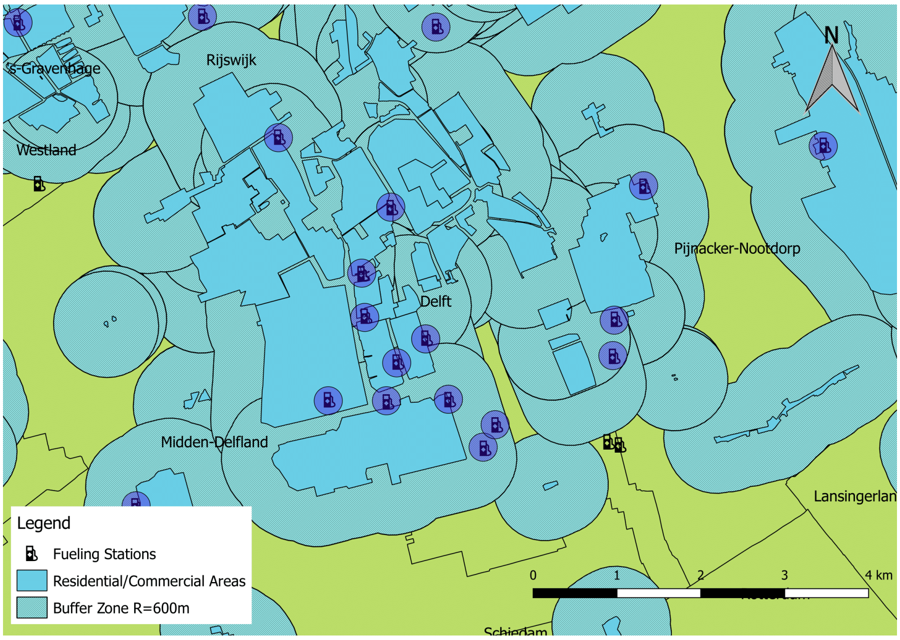


Figure 2.4: Filtering of fueling stations by a filter of a 600 m proximity radius to residential, commercial, and retail areas. Removed fueling stations (purple) around the Delft municipality.

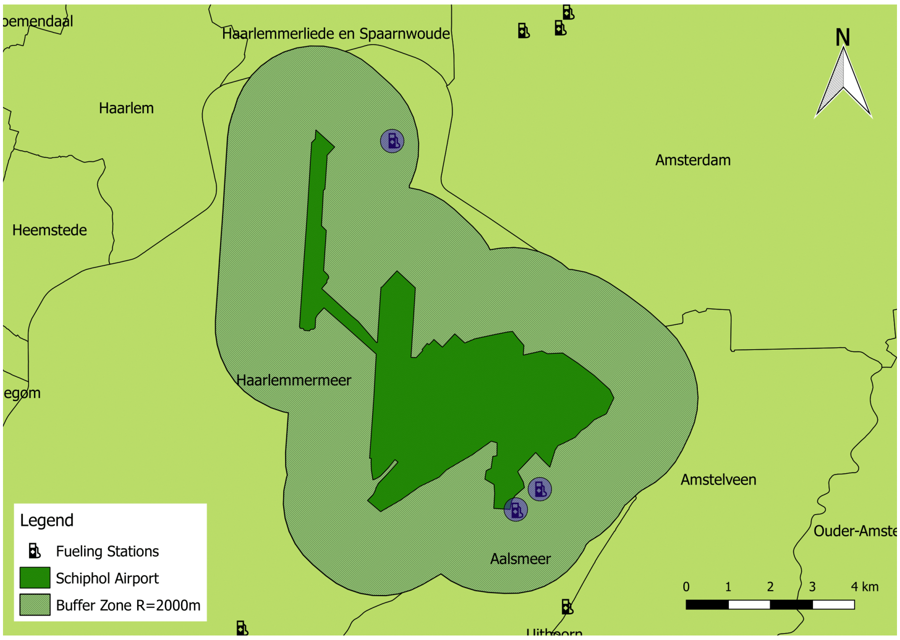


Figure 2.5: Filtering of fueling stations by a filter of a 2,000 m proximity radius to airport areas. Removed fueling stations (purple) around the Schiphol airport area.

the recommended setback distance for wind turbines was much larger that the average for other protected areas, with cases reaching 4 km, as mentioned by Winkelman *et al.* [33]. In total, protected sites contribute to approximately 8% of the removed fueling stations, as shown in Table 2.1.

The other protected site classifications showed no regulation regarding wind turbines in the surrounding areas, like national landscapes, provincial monuments or areas with restrictions for livestock. This was confirmed with the GIS datasets, shown in Figure 2.6, as there are wind turbines currently installed in a zone with geological value.

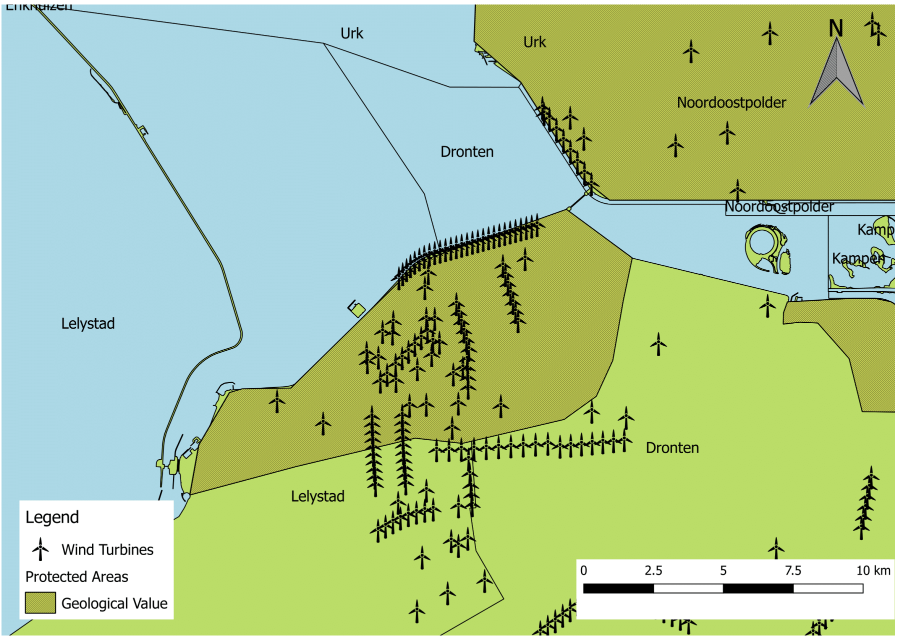


Figure 2.6: Wind turbines installed in zones of geological value in the Lelystad, Dronten, and Noordoostpolder municipalities.

SILENT ZONES

For silent zones, a setback distance of 1,250 m was defined using noise propagation simulations from a 5 MW wind turbine model from NREL. At 1,250 m, the magnitude of Sound Pressure Level (SPL) noise is between 40 and 45 dBa, up wind and down window the turbine [34, 35]. Figure 2.7 shows 3 fueling stations (marked with purple) removed from the feasible fueling stations due to the proximity to silent zones in the Midden-Delfland and Pijnacker-Nootdorp municipalities. This filtering step caused 1% of all the removed fueling stations.

It is important to mention that the silent zone filter considers the noise propagation patterns for 5 MW turbines. If smaller turbines were to be installed in fueling stations with lower demand, they could be placed closer to silent zones because of the noise reduction, therefore increasing the amount of feasible locations.

GEESE WINTER RESTING AREAS

Because of the variability of the bird protection areas, the recommendations of the Working Group of German State Bird Conservancies (LAG-VSW) were followed, using a minimum setback distance of 3,000 m for geese winter resting areas [36]. The study by Winkelman *et al.* [33], which is focused on The Netherlands, also has these recommendations due to the regional ecological importance of these birds. Figure 2.8 shows the results of this filter, which had a minimal impact by removing less than 0.5% of the petrol stations.

Figure 2.7: Filtering of fueling stations by a filter of a 1,250 m proximity radius to silent zones. Removed fueling stations around the Midden-Delfland and Pijnacker-Nootdorp municipalities.

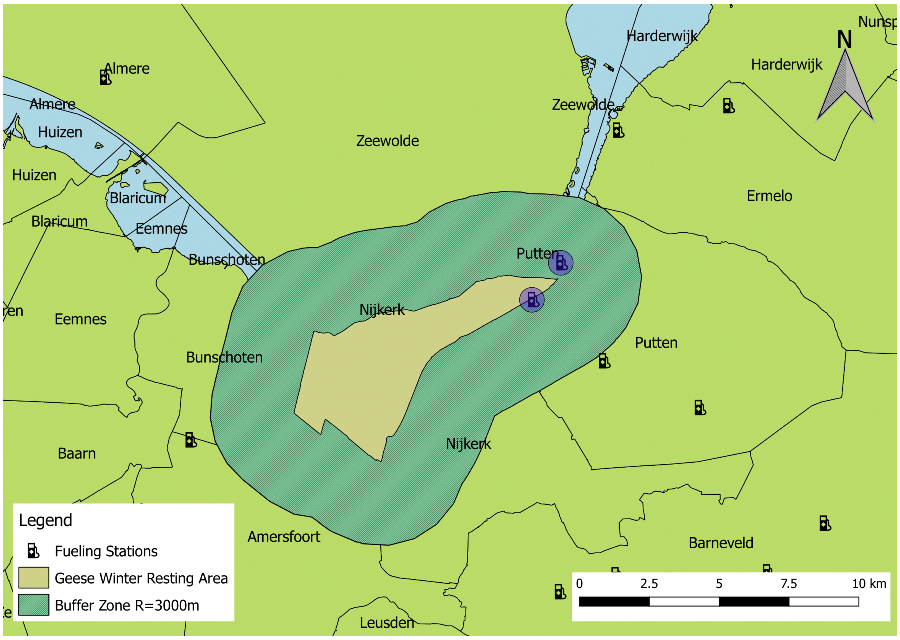


Figure 2.8: Filtering of fueling stations by a filter of a 3,000 m proximity radius to geese winter resting zones. Removed fueling stations around Nijkerk municipality.

ECOLOGICAL NETWORK

For the ecological area network, legislation regarding wind turbine placement is very case specific, because in some cases the environmental assessment only requires a setback of 300 m from forests, or in other cases, due to the proximity to bird migration areas, the required setback goes up to 4 km. After a review on the protection zones [36], and average current setback distances for wind turbines, a 1,200 m setback distance was defined. To have a notion of the current distances between installed wind turbines and ecological areas, the median distance between them was calculated at 1,535 m. This shows that the setback distance used is within the implemented in other wind energy projects. Figure 2.9 and Table 2.1 show that this filter causes around 6.5% of the removed fueling stations.

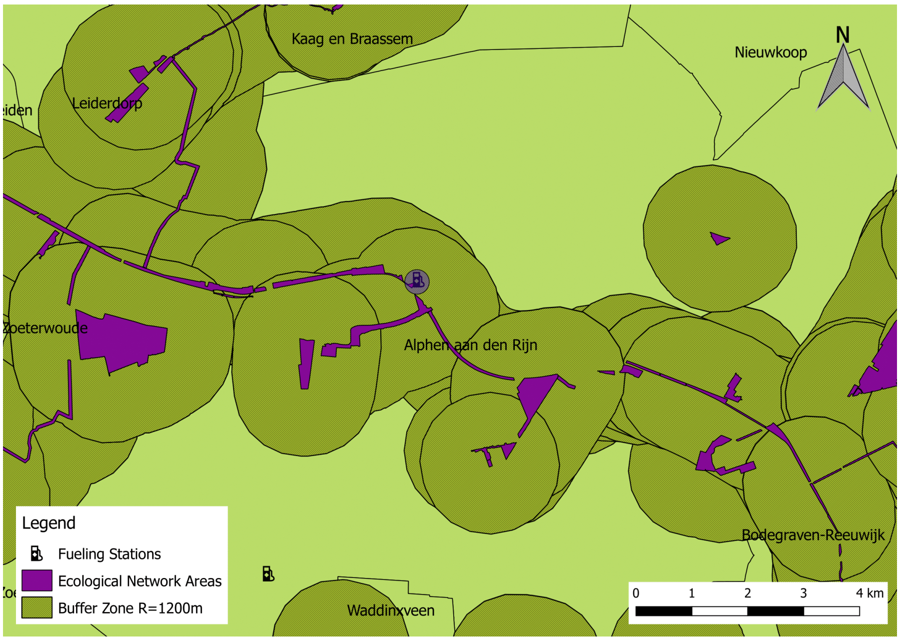


Figure 2.9: Filtering of fueling stations by a filter of a 1,200 m proximity radius to ecological network zones. Removed fueling station around Alphen aan de Rijn municipality.

2.3. EXISTING PETROL FUELING STATIONS SUITABLE FOR WIND TURBINE INSTALLATION

The two filtered datasets from OSM and GPS-POI were merged and duplicated locations were removed. Missing information was added using Google Maps, Google StreetView, Open Street Maps, and fueling companies websites. The final feasible fueling station distribution around The Netherlands is shown in Figure 2.10, with a total of **106** locations that are outside all the restricted areas according to current regulation. Table 2.2 shows the distribution per province, with some additional census information to provide an idea of the possible impact of HFSs in the area and the amount of people and vehicles that could use this energy carrier for transportation, heating, and backup electricity. The results from all the filtering steps are detailed in Table 2.1. The reduction values indicate the percentage of the removed fueling stations caused by each filter, to highlight which zoning restrictions are the most limiting for this proposal.

From Figure 2.10 it can be seen that Limburg, Noord-Brabant, and Zeeland are the provinces with the least amount of feasible locations, mostly due to the ecological network area restrictions and residential areas. Flevoland and Zeeland have a small number of fueling stations, most of them located in urban areas. Also, although Noord-Holland has 13 feasible locations, the second highest number (12.2%), most of them are located in the northern area of the province with low population density, as most of the population is located in the southern area (Amsterdam and Haarlem). Friesland has 27% of the possible locations in a zone with very low population density and high wind speeds between 7.5 and 9 m/s. This zone could overproduce hydrogen for large storage in salt caverns, transport to the Rotterdam port for exports, internal consumption, or as feedstock for the chemical industry [1].

There is a clear mismatch between the cities with high population density and heavy traffic roads, and

Table 2.1: Effect of zoning regulations on the amount of fueling stations suitable for wind turbine installation, for the Open Street Maps and GPS-POI databases.

Filter (setback distance)	**Open Street Maps**			**GPS-POI**		
	FS	**Removed FS**	**Reduction [%]**	**FS**	**Removed FS**	**Reduction [%]**
Initial	3,021	0	0	3,895	0	0
Wind turbines (200 m)	3,011	10	0.34	3,877	18	0.47
Residential/Commercial/Retail (600 m)	334	2,677	91.15	396	3,481	91.82
Airports (2,000 m)	325	9	0.31	383	13	0.34
Silent Zones (1,250 m)	296	29	0.99	348	35	0.92
Geese Winter Resting Zones (3,000 m)	284	12	0.41	339	9	0.24
Ecological Network (1,200 m)	84	200	6.81	104	235	6.20
Final results	**84**	**2,937**	**97.22**	**104**	**3,791**	**97.33**

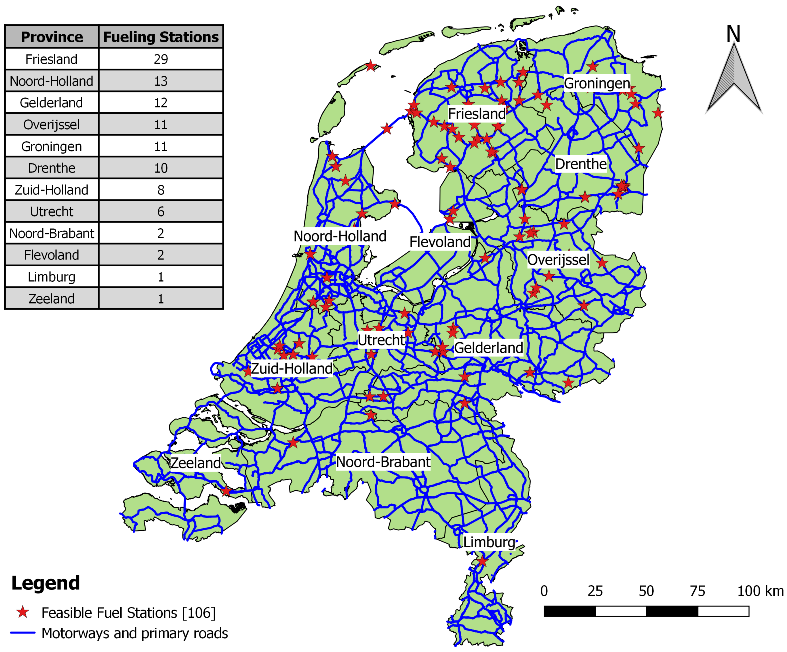


Figure 2.10: Distribution of fueling stations in The Netherlands suitable to install a wind turbine, per province.

the feasible locations. Utrecht has the highest traffic statistics in the country, as it is a main city in the center of the country and very well connected [37], but only has 6 feasible locations for a HFS with wind powered on-site generation. This means that if The Netherlands does change to a hydrogen based transportation fleet, large scale centralized hydrogen production plants would be necessary, although other means of sustainable electricity generation should be studied to have a mixed electricity source for hydrogen production.

According to standard IEC 61400-1:2005 [38, 39], wind turbines have the following classification: Class I (10 m/s), Class II (8.5 m/s), Class III (7.5 m/s), or Class IV (6 m/s). The wind speeds used for this classification were estimated at 159 m height, as manufacturers are increasing tower heights in order to reach higher wind speeds, while also using oversized rotors to capture more energy from the wind. Regarding the wind availability in The Netherlands, approximately 60% of the feasible locations have wind speeds higher than 6 m/s, as seen in the provincial wind class distribution of the filtered location in Table 2.2. From the 106 feasible locations, 42 have Class IV wind speeds and 48 have Class III wind speeds, meaning that a Class III wind turbine would be suitable for 85% of the selected locations.

Table 2.2: Feasible fueling station distribution per province, with census statistics from 2017.

Province	**Feasible Fueling Stations**		**Population**	**Population Density [Pop/km^2]**	**Personal Vehicles**
	Quantity	**Wind Class I/II/III/IV**			
Friesland	29	5/5/19/0	646,874	195	303,570
Noord-Holland	13	3/1/9/0	2,809,483	1,055	1,100,645
Gelderland	12	0/0/0/12	2,047,902	412	954,375
Groningen	11	0/0/10/1	583,581	251	251,825
Overijssel	11	0/0/0/11	1,147,687	345	536,125
Drenthe	10	0/0/1/9	491,792	187	250,170
Zuid-Holland	8	0/1/7/0	3,650,222	1,301	1,476,255
Utrecht	6	0/0/0/6	1,284,504	930	585,130
Flevoland	2	0/0/2/0	407,818	289	173,230
Noord-Brabant	2	0/0/0/2	2,512,520	511	1,233,830
Zeeland	1	0/0/1/0	381,568	214	192,130
Limburg	1	0/0/0/1	1,117,546	520	557,420

2.4. SUMMARY

The use of GIS tools was key to identify which locations are suitable for wind turbine installations. However, the main concern was with the interpretation of laws and regulations that stated the normative for wind turbine locations. Also, the veracity of this section's results is linked to the accuracy of the data sources, and as The Netherlands is in constant infrastructure development, the site conditions that make some locations suitable for the installation of a wind turbine can change in a small timespan.

Only 106 existing fueling stations can have a wind turbine installed, meaning that this is not a complete solution to the transition to hydrogen fueled transportation. However, due to the use of wind energy, it would be a step forward in order to reduce emissions from hydrogen generation. Around 45% of these locations (48 locations) have Class III wind speeds, while 40% are Class IV (42 locations). Also, there is a noticeable mismatch between the feasible locations, high population areas, and high traffic roads and highways, which means that hydrogen would required additional storage and transportation to connect hydrogen production and consumption sites.

The following Chapters provide a detailed analysis of the expected demand profile, the system components and configuration of the HFS, and techno-economical analysis of the recommended configuration based on the performance metrics evaluation. The results of this GIS study were used to select a location for the proposed HFS in order to have a realistic wind profile based on real wind data, adjusted with the surface roughness of the selected location.

3

HYDROGEN FUELING STATION MODEL PROPOSAL

Inputs, model components, and performance evaluation metrics

This Chapter details all the factors considered for the proposed HFS model in The Netherlands. Wind speeds from meteorological weather stations, wind power generation, and hydrogen demand in 2030 were considered to have an accurate representation of the hydrogen generation and consumption in the selected location. Different system configurations for the HFS were compared to consider under-sized, demand-sized and over-sized systems. Performance metrics allowed to quantitatively compare the systems using technical, economical, and environmental figures.

The model takes as variable inputs: the wind speeds and directions at hub height at the selected location, the wind turbine power output, and the expected hydrogen demand for a single HFS in 2030. These inputs were defined as variable because they change per hour of the year. The wind turbine power output is dependent on the wind speed at each specific hour and the wind turbine power curve. The efficiencies and costs of the components used for hydrogen production, compression and storage, distribution, and dispensing were considered as static inputs because the values were fixed, allowing to simplify the model.

3.1. WIND SPEED YEARLY PROFILE: LOCATION SELECTION

The Zoetermeer municipality was selected based on the feasible locations obtained from the GIS study in Chapter 2. This location has a high population density, high density of vehicles and mopeds, and the highest number of petrol fueling stations that comply with the requirements to install a wind turbine on-site. The wind speeds in this region are of Class III due to the proximity to the coast and flat terrain, as all the selected fueling stations are less than 20 km from the shore. As 45% of the selected locations have Class III winds, the class with the highest share as shown in Table 2.2, a system optimized for this wind availability is the most beneficial and representative for The Netherlands. The main limitation for the wind speeds is caused by the buildings in the urban areas, but the selected fueling stations in Zoetermeer are more than 3 km away from the city center, making the surrounding surface roughness similar the one in open areas.

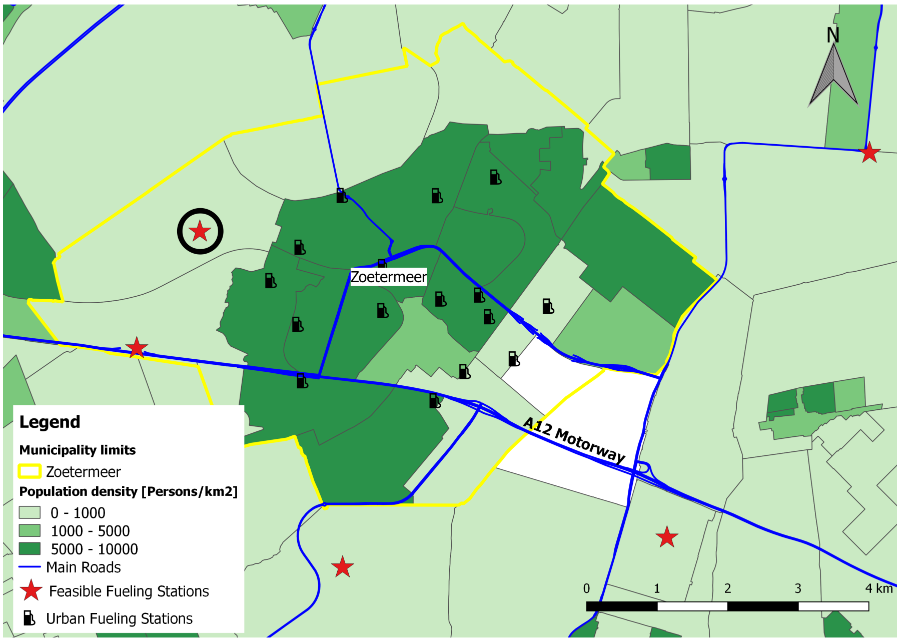


Figure 3.1: Feasible fueling stations around Zoetermeer, South Holland. The wind speed analysis was performed at the location marked with a black circle.

As seen in Figure 3.1, there are 5 fueling stations around the urban area of Zoetermeer which are close to the A12 motorway and other main roads. Zoetermeer has 16 petrol fueling stations located in its urban area. In the future, some of these fueling stations could be distribution points for hydrogen to avoid people travelling outside the city to refuel their FCEVs.

Although Zoetermeer has 5 feasible locations, only one HFS was modelled. The demand profile detailed in Section 3.2 was compared to the amount of vehicles in Zoetermeer just to estimate the potential share of the local passenger vehicle fleet that could refuel hydrogen in these surrounding stations.

3.1.1. WIND SPEED PROFILE IN ZOETERMEER

As the proposal contemplates that most of the energy consumed by the HFSs will be produced with wind energy, the analysis of the wind speeds in Zoetermeer was key to know the potential of the proposal and the selection of the wind turbine to be used. The location marked with a black circle in Figure 3.1 was used for the wind speed analysis.

Hourly data of wind speed and orientation measured in 2015, 2016, and 2017 was taken from the online database of the Royal Netherlands Meteorological Institute (KNMI) [40], and then scaled to the hub height of the wind turbines detailed in Section 3.4.1. For the three year period, the average speed and median wind direction were calculated. The median is used for the wind direction because the data is recorded in values from 0° to 350°.

The closest weather station to Zoetermeer with complete information is located in Voorschoten, in an area surrounded by grass and few obstacles. This weather station is 8 km to the east from Zoetermeer. In the weather station, wind speed is measured at 10m height, this data had to be extrapolated to the wind turbine's hub height using the power law (Equation 3.2) and logarithmic law (Equation 3.1) [41].

$$U(h) = U(h_{ref}) \cdot \frac{Ln\left(\frac{U_h}{z_0}\right)}{Ln\left(\frac{U_{ref}}{z_0}\right)} \quad (3.1)$$

$$U(h) = U(h_{ref}) \cdot \left(\frac{U_h}{U_{ref}}\right)^{\alpha} \quad \alpha = 0.143 \quad (3.2)$$

Roughness profiles were considered for the specific locations of the weather station and the five feasible petrol fueling stations in Zoetermeer, resulting in 6 sites with different roughness patterns. This was done to identify possible obstacles in all locations before extrapolating the wind speed data from the weather station. Using GIS, the terrain elevation was sampled for all the 5 feasible fueling stations to calculate the terrain roughness in every direction. Samples were taken 2 km around each location due to computational contraints, although experimental data recommends distances between 3 to 5 km [42]. Each radius was separated by 10°, for a total of 36 straight lines. Measurements were taken every 50 m along each radius, for a total of 1,440 elevation samples on around each location.

Taking the average variation between samples, the feasible fueling station with the highest roughness was selected to assume a pessimist wind speed profile. A roughness value was empirically assigned to each wind direction based on Table B.2. The ratio between the distance to the center point and height of the obstacle was used to determine the surface classification, as well as available satellite images from the location.

The logarithmic law was used to extrapolate the wind speeds from the weather station, from 10 m to 60 m height. This was done with equation 3.1 to reach wind blending height. At this height, depending on the size of the obstacles, the wind speeds are not affected by local terrain roughness [42]. Hourly wind speeds were extrapolated according to the wind direction and surface roughness, resulting in a wind speed profile at 60 m height.

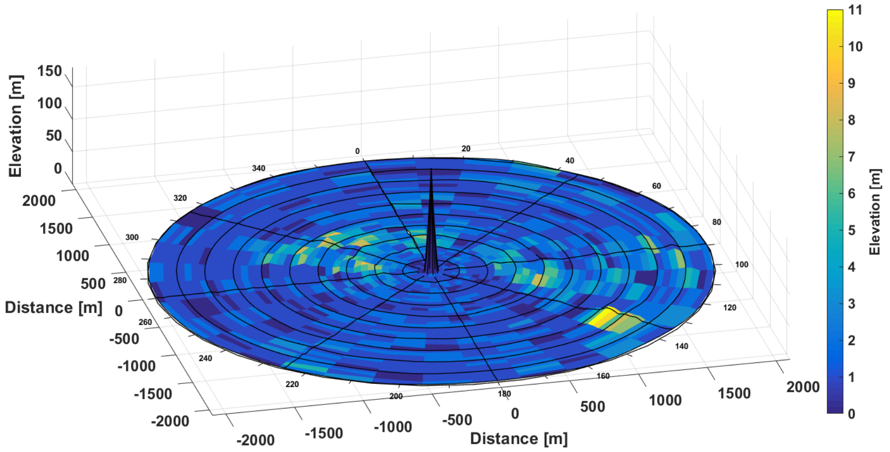


Figure 3.2: Terrain roughness profile for the HFS in Zoetermeer, in a 2 km radius. The center peak represents a wind turbine with a hub height of 160 m. North=0°.

Due to the low surface roughness in the selected fueling station, composed mostly by grass land, the wind speeds at 60 m were assumed to be equal to the ones measured by the weather station at 60 m. Figures B.1 and 3.2 show both elevation profiles detailing the difference between the height of the measurement point and the surface roughness, with the center at 10 m (measurement height) for the Voorschten weather station and 159 m (estimated hub height) for the feasible fueling station.

Finally, the power law was used to extrapolate the wind speed from 60 m to 159 m (Equation 3.2). For neutral atmospheric stability, the exponent α is defined at 0.143 for the The Netherlands [42].

With all the considerations mentioned above, the wind rose shown in Figure 3.3 shows the expected wind speeds in the selected HFS location. The results from the adjusted wind profile were used as the input wind profile on an hourly basis. South-west winds are predominant, as expected due to the wind patters in the region [42]. Also, wind speeds between 5 m/s and 15 m/s account for more than 75% of the measured wind speeds, with 7.1 m/s as average wind speed.

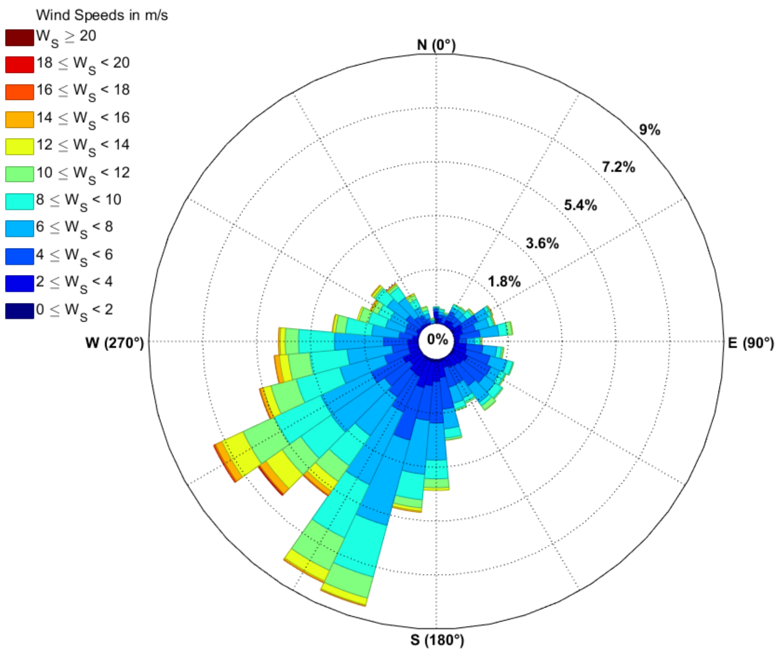


Figure 3.3: Wind rose for Zoetermeer at 160 m height, considering data from the years 2015 to 2017 and surface roughness.

3.2. HYDROGEN DEMAND OF A DUTCH HFS IN 2030

Currently, The Netherlands only has pilot projects with fuel cell vehicles or newly installed HFSs, therefore there is no data available on real consumption profiles of retail HFS [12]. However, there is information available about petrol consumption profiles from existing fuel stations, data from Dutch petrol fueling stations, and vehicular fleet statistics from The Netherlands. Also, NREL, from the USA, publishes annual data from the 31 retail HFS currently operating in the state of California [27].

This allowed to perform 2 different extrapolations to estimate the hydrogen consumption in 2030. The first one was based on the assumption than in 2030, a HFS will supply enough hydrogen for the same amount of users to travel the same distances as with a petrol fueling station. The amount of driven kilometers with the dispensed petrol was used as the reference point. This method is explained in Section 3.2.1.

The second method consisted in calculating the annual growth trend of annual dispensed hydrogen in HFSs in USA. This method assumes that the hydrogen consumption pattern from The Netherlands will be the same as in the USA. The results from this extrapolation, presented in Section 3.2.2, allowed to corroborate that the first extrapolation method had realistic and comparable values.

3.2.1. HYDROGEN DEMAND BASED ON THE AVERAGE FUEL DISPENSED BY A DUTCH PETROL STATION

The aim of this method was to calculate the amount of H_2 necessary for users be able to travel the same amount of kilometers during the year with FCEVs than with ICE vehicles. The average dispensed petrol from a Dutch petrol station was converted into driven kilometers with the average efficiency of the Dutch vehicular fleet. This value was linearly extrapolated to 2030 with the annual growth of driven distance in The Netherlands. Finally, the value was converted to kilograms of hydrogen with the expected efficiency of FCEVs in 2030. The extrapolation procedure is shown in Figure 3.4.

In 2011, the average Dutch fueling station dispensed 2,182,000 liters of petrol [43]. These were manned (non-automated) fueling stations, which represent 75% of the fueling stations in The Netherlands [43]. According to the Netherlands Organisation for Applied Scientific Research (TNO), the average efficiency of internal combustion vehicles in The Netherlands is around 7 litres/100km [25] [44]. This means that, in 2011, an average Dutch fueling station supplied enough fuel to travel 31.17 million kilometers.

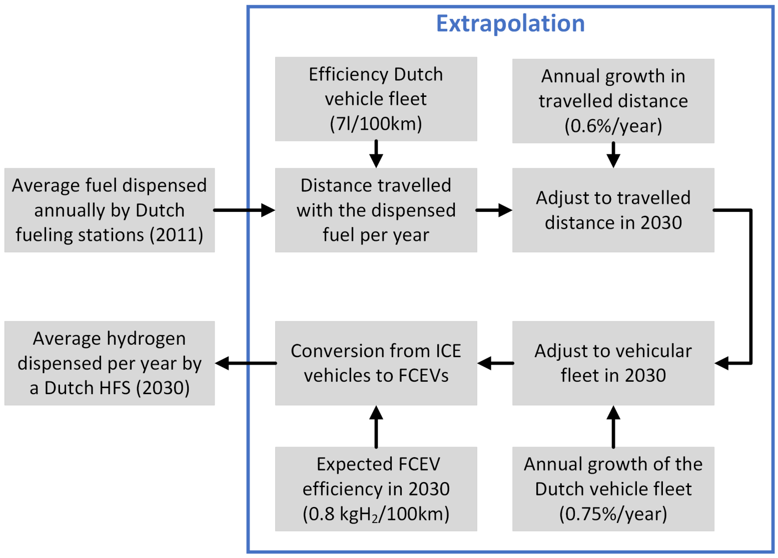


Figure 3.4: Extrapolation process to calculate the demand from a Dutch HFS in 2030.

The travelled distance by Dutch passenger cars has increased by approximately 0.8% per year in the last 20 years, reaching 37 km/day in 2017 [45]. Also, since 2000, the average annual growth in the Dutch vehicular fleet has been 1.75% per year. Considering future inclinations for car sharing services and autonomous driving, the increase in driving distance from 2017 to 2030 was estimated at 0.6%/year, and the increase in the fleet to 0.75%/year.

These values allowed to consider that in the future there will be more cars that will refuel more often. Following these linear trends, an average Dutch fueling station in 2030 should supply enough fuel to travel 40.32 million kilometers.

Although the efficiency of FCEVs in 2018 was around 1 kgH_2/100km [46–49], the Hydrogen Council estimates a future 30% decrease in hydrogen consumption. For this model, FCEV efficiency was considered at 0.8 kgH_2/100km in 2030. Using this efficiency, and converting the total amount of kilometers that should be travelled, an average Dutch hydrogen fueling station should supply 302,560 kgH_2 in 2030.

3.2.2. DISPENSED HYDROGEN IN HFS IN USA

To corroborate that the annual hydrogen demand calculated in Section 3.2.1 is within the expected values, the demand in a HFS in USA was extrapolated to 2030. Dispensed hydrogen shows a considerable growth, from 104 H_2tons in 2016 to 438 H_2 tons in 2017 [27]. Every year, more HFS are installed and more FCEVs are available in the market. A second degree polinomial extrapolation from 2016 to 2030 was used with the information published by NREL, which details the average dispensed hydrogen from the 31 existing HFS [27]. The introduction of the Toyota Mirai in California in 2016 initiated the increase in dispensed hydrogen in these HFSs. The extrapolation resulted in an expected amount of hydrogen dispensed of 713,186 kgH_2 per HFS in 2030.

In 2017, the average travelled distance per driver in USA was 21,516 km, 59% more that in The Netherlands [50]. Also, California has over 25 million passenger vehicles registered [51]. Given the difference in driven distance and total amount of vehicles in California compared to The Netherlands, a HFS with more than double the capacity calculated in Section 3.2.1 is expected. However, this number doesn't consider the installation of new HFS or introduction of new FCEVs in the market (currently the Toyota Mirai, Honda Clarity FCEV and the Hyundai ix35 FCEV). This extrapolation indicates that 302 H_2tons is a realistic annual demand for a Dutch HFS in 2030, as calculated in Section 3.2.1.

3.2.3. DUTCH HYDROGEN CONSUMPTION PROFILE

A demand of 302,560 kgH_2 per year was used in the HFS model, as calculated with Dutch transportation trends in Section 3.2.1. On average, each passenger vehicle will travel 14,600 km and consume 116.8 kgH_2 in 2030. With the calculated demand for the HFS, a total of 2,590 FCEVs could be fueled per year. This is within the range of the small European city characteristics of 1 petrol station for 2,300 passenger vehicles, although the consumption from large vehicles like lorries or buses is not included [52]. The hydrogen consumption from scooters was not considered due to their low consumption (1.8 gH_2/km [53, 54]) and short distances travelled (2.6 km/day [37]).

NREL compared current HFS data from 2016 and 2017 to the fueling profiles from Chevron [27, 55]. Daily fueling patterns are similar, although hydrogen dispensing peaks in the evening instead of midday. The weekly hydrogen consumption is more concentrated during the weekdays, with lower demand during the weekends. On average, each HFS in California dispensed around 50 kgH_2 per day in 2017, with some HFSs reaching up to 100 kgH_2 per day. For the hydrogen demand profile, the Chevron weekly patterns were used, as hydrogen dispensing is expected so have a similar behaviour in 2030.

The yearly demand was adjusted to create an hourly demand profile. This profile takes hourly consumption variations for every day of the week, the consumption in every day of the week, and the seasonal fluctuations in demand. Seasonal fluctuations from the Chevron consumption profile were considered, as summer and winter months show a 10% increase and decrease in total transactions [56], respectively. This is assumed to be caused by people driving more due to better weather, thus spending more time outside their homes. To adjust for this behaviour, the total consumption in winter months was set 10% lower that the average, summer months were set to 10% more consumption than the average, and spring and fall were set to the average consumption. The increase and decrease between seasons were made in 1% steps to avoid abrupt changes, as shown in Figure 3.5.

Weekly variations were also considered with the Chevron profiles. The variation between transactions between weekdays and weekends shows a higher consumption during the weekends, probably due to leisure activities. The share of transactions per day during the week is shown in Figure 3.6.

For the daily fluctuations, it was assumed that in 2030 there will be enough FCEVs for the consumption patters of hydrogen and petrol to be equal. Most fossil fuel companies don't share their exact sales and vol-

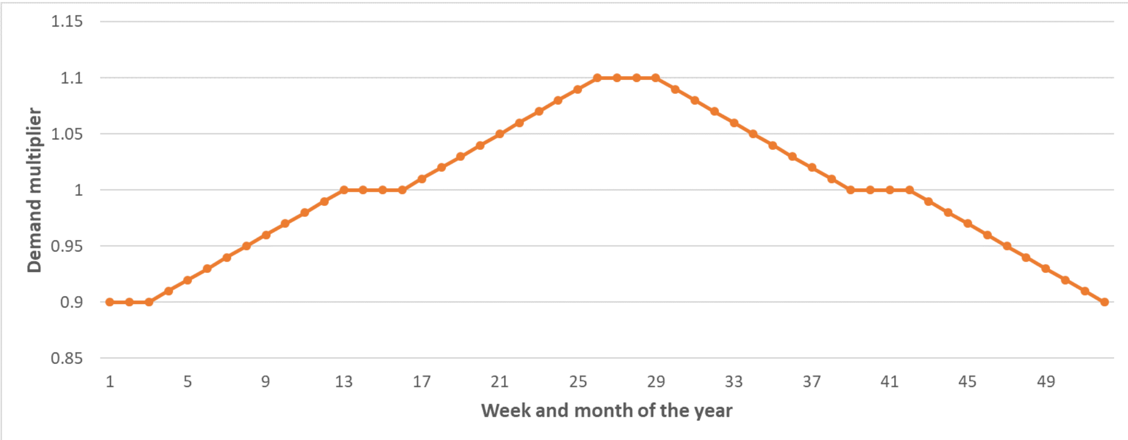


Figure 3.5: Seasonal fluctuation adjustment for every week of the year. A demand multiplier of 1 means that the weekly average demand is used.

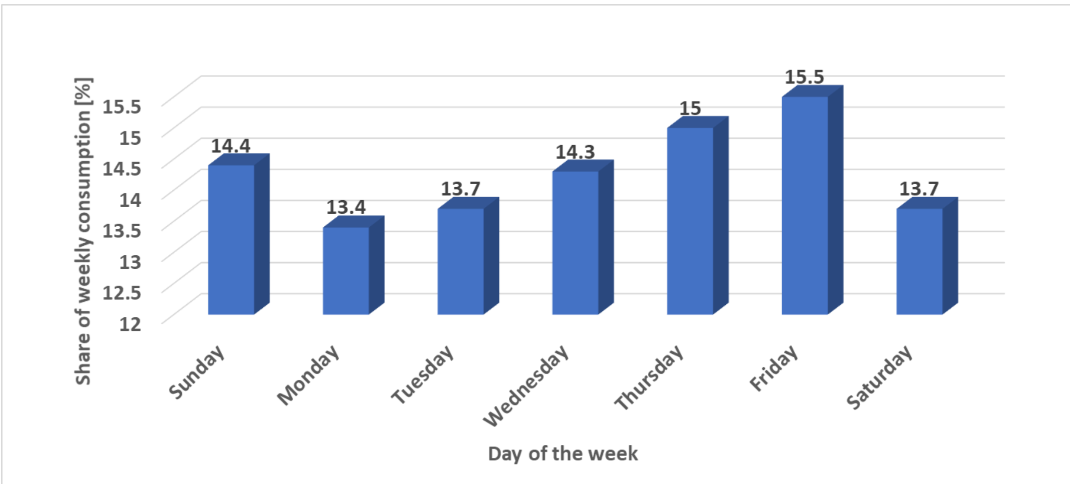


Figure 3.6: Weekly transactions per day of the week, based on 387 Chevron fueling stations located in The United Stated [56].

umes, but Chevron published information about the average amount of transactions per hour of the week from 387 fueling stations located in The United Stated, as detailed by Chen [56]. These daily patterns, as shown for 3 days of the week in Figure 3.7, were used to scale the extrapolated hydrogen demand in 2030.

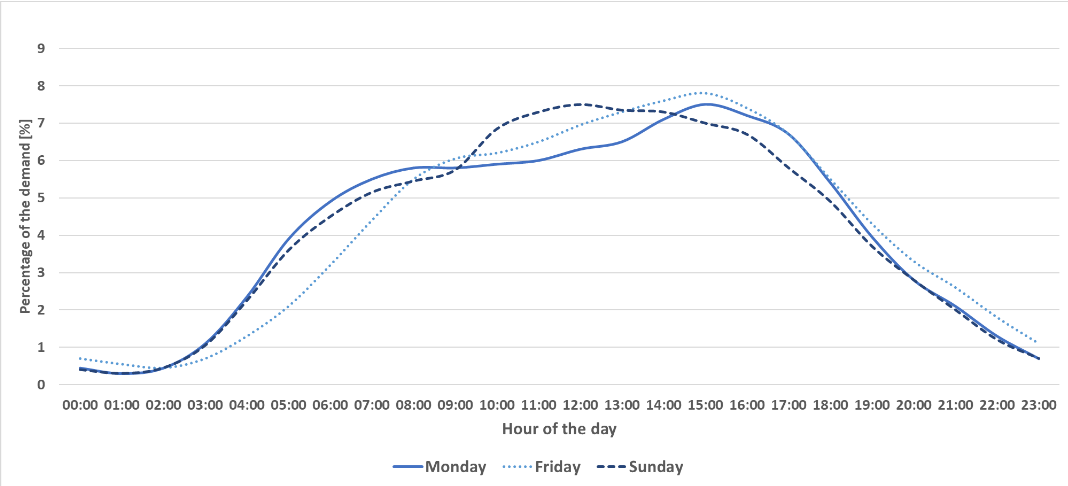


Figure 3.7: Hourly share of transactions in different days of the week, based on 387 Chevron fuelling stations in The United States [56].

Using registered vehicle data from 2017, the Zoetermeer municipality currently has 56,506 passenger vehicles [57]. With a passenger vehicular fleet growth, the city could have 62,270 passenger vehicles in 2030. Conservative studies assume a 10% market penetration from FCEVs in 2030 [58, 59]. The Hydrogen Coucil estimates that around 3% of the new passenger vehicles sold in 2030 will be FCEVs [49]. As a comparison, the proposed HFS could supply 2,590 FCEVs, which would be 4.1% of the vehicles in Zoetermeer in 2030.

The expected average daily consumption for the HFS is 829 kgH_2. Considering the weekly and seasonal factors, the daily demand fluctuates between 700 kgH_2 on a winter Monday and 989 kgH_2 on a summer Friday. This behaviour is shown in Figure 3.8.

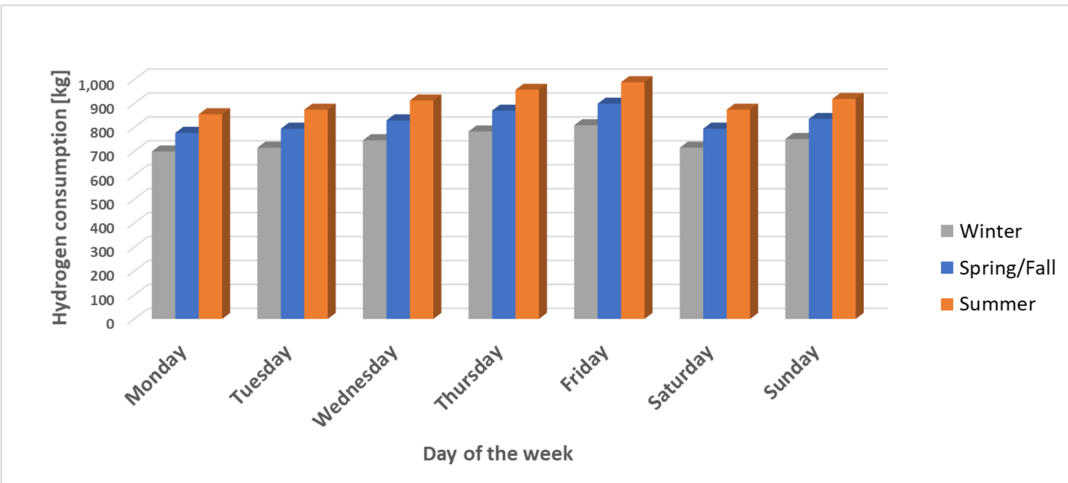


Figure 3.8: Estimated weekly demand of a Dutch hydrogen fueling station in 2030, for the different seasons of the year.

3.3. HYDROGEN FUELING STATION MODEL

The model was simulated using Matlab. The diagram in Figure 3.9 shows the basic flow of data for the yearly calculations of hydrogen production and storage. To simplify the model, the level of the high pressure tanks is not calculated. Therefore, the storage tank mentioned is the medium pressure tank. The definition of constants sets the efficiency and costs for all the components in Section 3.4. The files with wind speed, hydrogen demand and wind turbine power curves are also loaded in this initial phase.

For every hour of the year, the calculations performed are detailed below. Initially, the hydrogen demand in each hour is removed from the tanks. Then, the hydrogen left in the tanks is calculated, leaving the available space in the tanks to store the hydrogen produced by the electrolyzer. The available electric energy is calculated per hour with the wind speed and wind turbine power curve. Additional to this, the grid capacity for the selected configuration is added. With the efficiency and capacity of the electrolyzer, this results in the maximum hydrogen production at each specific hour. The hydrogen produced is either limited by the electricity supply (wind + grid) or the available space in the storage tanks.

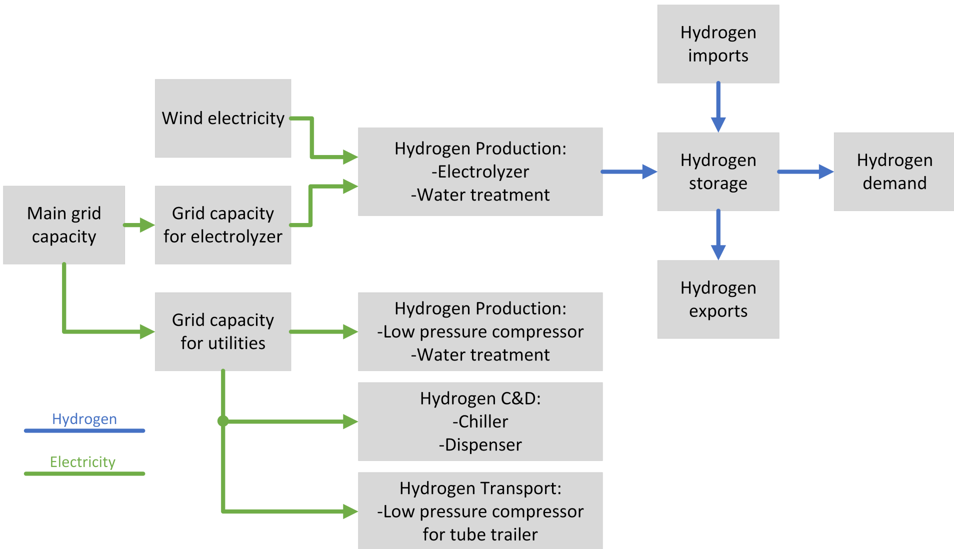


Figure 3.9: Simplified flowchart of the Matlab model in terms of the hydrogen production, storage, imports and exports.

After producing and storing the hydrogen, the model calculates if its necessary to buy or sell hydrogen according to the storage tank levels. Hydrogen quantities of 500 kgH_2 are bought or sold when the storage tank are below 10% or higher than 90% capacity. A tube trailer is used for this purpose. Finally, the storage tank level is updated if hydrogen was bought or sold.

After the complete year has been calculated, the yearly values are used to calculate the metrics for the lifetime of the HFS. The electricity used in production, compression and dispensing is also calculated per hour of the year to accurately calculate the electricity demand. Surplus electricity is sold using the available grid capacity, if not, it is curtailed.

3.3.1. MODEL CONSTRAINTS

The model has constraints in order to facilitate the simulation process. The main one is related to the efficiency and electricity consumption from the main components of the hydrogen generation, compression, and dispensing system. Fixed efficiency values were used instead of load dependent values. The efficiency for this processes is therefore taken as a constant value.

The storage tanks are set to 100% capacity at the beginning of the year. Also, the hydrogen purchases or sales are assumed to be executed within one hour. Currently this is not possible due to compressor capacities, but it is expected to improve in the coming years [52].

High pressure storage tanks are considered part of the dispenser system and therefore not considered for the hydrogen consumption-production balance. They are taken into account when calculating the costs of the system.

In terms of the economic data, based on literature, there is a gap between current industry prices and literature. Most literature is based on pilot projects of HFSs that don't account for economies of scale, and most prices of components are not disclosed. Also, most prices are based on the component and exclude installation costs.

3.4. COMPONENTS OF THE PROPOSED HFS SYSTEM

The sizing of the system components was based on the demand profile, aiming to match hydrogen generation and demand. The problem with wind energy in The Netherlands, according to the measured wind speeds in Zoetermeer (Figure 3.3), is that the generation profile is lower in the summer, when the hydrogen consumption for vehicles is higher. After some initial simulations, it was decided that the best strategy was to define a set of component sizes for the grid capacity, number of wind turbines, and electrolyzer capacity. This way, multiple system configurations were simulated and evaluated with the metrics defined in Section 3.5. The selected component capacities were in line with market ready equipment. Initial investment for all the components is referred to as CAPEX, and the operational and maintenance costs as OPEX. The OPEX is a percentage of the CAPEX that covers the annual costs of operation and maintenance of the equipment.

The sizing of the components was based on the demand profile and wind availability. Also, taking all the HFS components, the wind turbine options were selected to cover most of the required energy within the year. Based on the expected demand from Section 3.2.1, the following components capacities were selected: 5 electrolyzer capacities of 15, 25, 35, 45 and 55 kgH_2/hour (800 kW, 1.4 MW, 1.9 MW, 2.4 MW, and 3 MW, respectively.); one wind turbine of 3.5 MW or 4.2 MW; and a grid capacity for the electrolyzer and wind turbine between 0 MW and 4 MW. Grid capacities were simulated in 500 kW increments to understand the impact of the grid capacity on the HFS technical and financial performance. Due to the required electricity to compress and dispense the produced hydrogen, a minimum grid capacity was defined for utilities according to the electrolyzer capacity.

3.4.1. WIND TURBINE SYSTEM

The wind turbine is the main electricity supplier for the HFS. The electricity generated is used to power the complete facilities. If more electricity than the required by the HFS is available, it is sold to the grid to make additional profit.

The wind turbines from Enercon were chosen for the simulation. The selected models are detailed in Table 3.1, for the 3.5 MW and 4.2 MW capacities with a hub height of 159 m. These were chosen because Enercon is one of the main wind turbine manufacturers in Europe [60, 61], and the power curves for both wind turbines were available in the manufacturer's website [62, 63].

The highest hub height was selected to increase electricity generation because of higher wind speeds. The efficiency of the entire system was estimated in 95% to account for mechanical, and electrical losses in the system [64]. The CAPEX of onshore wind turbines was assumed at 1,100 €/kW and the OPEX at 2.8%/year of the capital cost [52, 65].

In the model, the system used one of the selected turbines, installed in the vicinity of the HFS. The distance between the wind turbine and the HFS was assumed to be 300 m, to account for the interconnection costs of the system.

Table 3.1: Technical specifications for Enercon wind turbines of 3.5 MW and 4.2 MW [66].

Specification	E-138 EP3	E-141 EP4
Rated power	3.5 MW	4.2 MW
Hub height	159 m	159 m
Cut-in speed	2.0 m/s	3.0 m/s
Rated speed	14 m/s	14 m/s
Cut-out speed	30 m/s	34 m/s
Wind class	IIIa	IIa

ELECTRICITY GENERATION

To calculate the yearly electric energy that could be generated from the two wind turbines models, the power curves for the Enercon E-141 EP4 4.2 MW and Enercon E-138 EP3 3.5 MW were taken from the manufacturer technical data. Both power curves are shown in Figure 3.10 [62, 63]. With the wind speed profile for Zoetermeer calculated in Section 3.1.1, the electricity generation was 13.05 GWh for the 3.5 MW wind turbine and 14.5 GWh for the 4.2 MW wind turbine. These results imply capacity factors of 0.42 and 0.39, respectively.

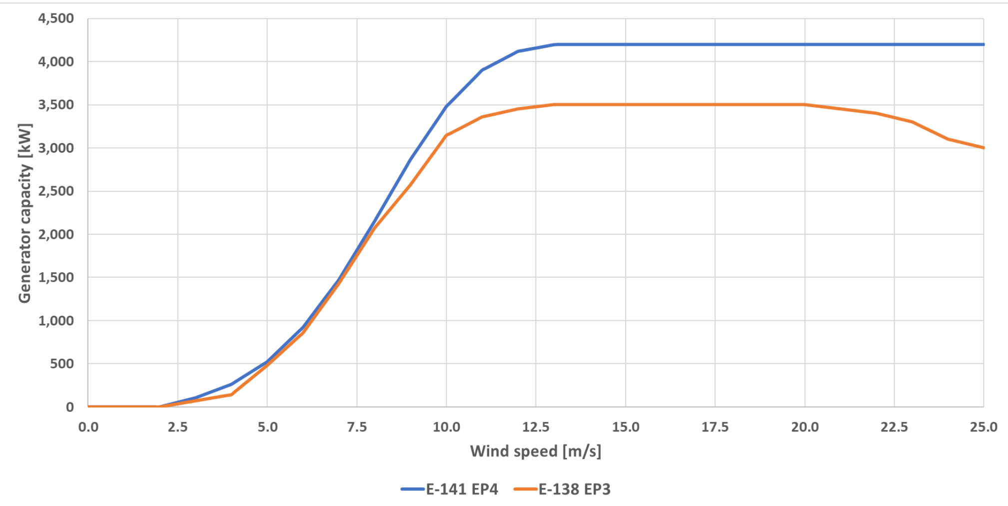


Figure 3.10: Power curves for the Enercon E-141 EP4 and Enercon E-138 EP3 wind turbines, with a hub height of 159 m[62, 63].

3.4.2. INTERCONNECTION TO ELECTRIC GRID

The grid connection was divided in 2 categories, utilities and production. The connection capacity for the utilities was estimated with all the HFS equipment, besides the wind turbine and electrolyzer, running at full power. This contemplates the case were all the compressors and dispensers are working when the wind speed is too low. The utilities grid capacity varied between 823 kW and 863 kW, considering that a higher H_2 production requires more consumption from the C&S stage. The wind turbine and electrolyzer grid connection was simulated from 0 MW to 4 MW capacity in 500 kW steps. This was done to understand the effect of the grid capacity on hydrogen price and HFS reliability.

The connection costs were taken from Stedin [67], the DSO in Zoetermeer, and were adjusted with an annual inflation of 1.5% until 2030 [68]. Prices per connection capacity are shown in Table 3.2. Surplus electricity is sold to the grid at this price to have additional revenue. However, the price of electricity when selling or buying is different. When buying electricity from the grid, the industrial price of 4.7 €/MWh was used, at the appropriate electricity consumption category [69].

According to information provided by Stedin [70], about 80% of the fueling stations in their area have 3x80A connections (55 kW). The remaining 20% has either 3x125A (86.5 kW) or 3x250A (173 kW) grid connections, mainly for Electric Vehicles (EVs). These grid connections don't have the capacity for the required equipment, making necessary the installation of a new or complementary grid connection.

Table 3.2: Grid connections costs for different capacities from Stedin, adjusted with inflation to 2030 [67].

Cost component	**2018**		**2030**	
Price per kWh for large users	€0.04		€0.0478	
Installation	**Fixed cost**	**Per meter**	**Fixed cost**	**Per meter**
630 kVA to 1,000 kVA	€37,202.49	€89.45	€44,479.97	€106.95
>1,000 kVA to 1,750 kVA	€45,677.73	€92.24	€54,613.12	€110.28
>1,750 kVA to 3,000 kVA	€193,163.71	€125.29	€230,950.04	€149.80
>3,000 kVA to 10,000 kVA	€263,915.76	€143.55	€315,542.48	€171.63
Annual connection fee	**Fixed cost**		**Fixed cost**	
>175 kVA to 1,750 kVA	€674.86		€806.87	
>1,750 kVA to 3,000 kVA	€1,427.53		€1,706.78	
>3,000 kVA to 10,000 kVA	€7,369.08		€8,810.61	
Electricity Transport	**Fixed cost**	**Per max kW**	**Fixed cost**	**Per max kW**
151 to 1,500 kW	€441.00	€25.96	€527.27	€31.04
>1,500 kW	€2,760.00	€51.12	€3,299.91	€61.12

The distance from the existing medium voltage transformers was estimated at 300m. This was the average distance measured with GIS, between existing fueling stations and medium voltage transformers in the Zoetermeer area. Installation costs vary according to the required capacity and the distance from the connection point to the medium voltage transformer. At higher grid capacities, there are periodic costs for electricity transport and maintenance for the grid and transformer [67].

3.4.3. ELECTROLYZER

The electrolyzer is the main component of the proposed HFS, as it is the component that produces gaseous hydrogen and oxygen out of purified water and electricity. For this proposal, oxygen is a by-product that is not used and therefore released to the atmosphere, but in the future it could be stored, purified and sold.

Currently, there are two electrolyzer technologies leadint the market in terms of maturity and commercial availability: Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Water Electrolysis (PEMWE) [52]. AWE has been commercially mature for decades and has a lower specific electricity consumption than PEMWE. Low hydrogen costs are usually reached with AWE, specially with large installed capacities (over 2 MW)[71, 72]. However, through a recent increase in R&D investment, PEMWE has acheived a better adaptability to fluctuating energy sources like wind or solar energy [73, 74]. This adaptability comes from power ramp ups of up to 200 kW/s [75], and response in the miliseconds range [72]. AWE is capable of adjusting the power demand in seconds, which is also acceptable for the proposed model [76]. Another benefit of PEMWE is the possibility to operate at higher current densities and pressures than AWE, eliminating the need for an additional compressor, depending on the application [72, 73, 75]. PEMWE shows the highest efficiency improvements and price reductions in the future [72]. However, as the proposed model uses a wind turbine, which has rotational inertia, and a grid capacity to level important fluctuations, AWE could also be considered. PEMWE is more suitable for direct connection to solar photovoltaic systems that have electricity generation changes in short times, due to clouds or shades.

As a final consideration, the capacity of PEMWE is available between 10-100% [72]. This is another benefit from PEMWE over AWE, as alkaline electrolyzers have better performance when used at over 30% of their rated capacity [72, 75].Because of this, and the mostly likely large scale adoption of PEMWE around 2030 [76], PEMWE was selected for this model.

PEMWE currently has an efficiency of around 70%, based on HHV. The predictions for 2030 indicate an HHV efficiency of around 75%, which translates to a specific electricity consumption of 53.4 kWh/kgH_2 [52, 72, 75].

The hydrogen produced by the electrolyzer needs additional purification to maintain the fuel cell lifetime of the FCEV, consuming an additional 1.3 kWh/kgH_2 [52]. The input water for the electrolyzer needs to be purified to avoid contaminating the internal membrane [77]. Average pure water consumption for an electrolyzer is 12 l/kgH_2 [78]. The consumption of reverse osmosis water purification system was estimated at 0.0056 kWh/kgH_2 [52]. The complete electrolyzer system is assumed to have a total specific electricity consumption of 54.7056 kWh/kgH_2.

Recent research and development on electrolyzer technologies, especially in manufacturing processes and power capacities, are makign important cost improvements every year [75]. The estimated CAPEX (considering 10% for installation costs) of the PEMWE electrolyzer in 2030 is 840 €/kW, with a 4% OPEX and 20 years of component lifetime [76]. However, the stack lifetime was defined at 80,000 hours assuming full load operation. The cost of the stack in 2030 was estimated at 30% of the CAPEX [71, 76]. The reverse osmosis system to purify water was assumed to have a CAPEX of 1.2 €/l/day, and an OPEX of 4.8% [52].

A range of electrolyzer capacities for the simulation were defined based on the demand calculated in Section 3.2, of 302,560 kgH_2/year. The electrolyzer has to produce an average of 34.54 kgH_2/hour throughout the year to meet the average demand. With the estimated efficiency, this electrolyzer needs an installed capacity of 1.85 MW. The simulated electrolyzer sizes correspond to approximately 50%, 75%, 100%, 125% and 150% of the average demand to model undersized and oversized electrolyzers. These corresponds to 5 electrolyzer capacities of 15, 25, 35, 45 and 55 kgH_2/hour (800 kW, 1.4 MW, 1.9 MW, 2.4 MW, and 3 MW, respectively).

3.4.4. LOW AND HIGH PRESSURE HYDROGEN COMPRESSORS

There are multiple options to compress hydrogen in the market, from mechanical to electrochemical compressors. A common used type is the diaphragm or membrane compressor, usually found in oil refineries to pump natural gas. The problem with this technology is that it was initially designed for full load operation, and a HFS requires intensive start and stop operations that greatly increase the need for maintenance [79]. Electrochemical and ionic piston compressors are preferred because of their high reliability and efficiency, reduced noise, and no contamination from lubricants [80–83].

Hydrogen needs to be compressed in 2 stages in the proposed HFS. The first stage is from the electrolyzer to the medium pressure storage tanks at 200 bar. Then, hydrogen is compressed again to 875-1,000 bar in the high pressure stage. Considering that these systems need to be as efficient as possible, electrochemical compressors were selected for the low pressure stage. Currently, only Hyet Hydrogen [84] commercializes this type of compressors, reaching up to 1,000 bar in one stage.

For the high pressure compression, the Ionic Compressor (IC90) developed by Linde AG. was selected [85]. This high efficiency compressor has only 8 moving parts and allows to increase the pressure up to 1,000 bar with a very high flow rate. Hydraulic pistons compress the hydrogen with ionic fluid as a barrier to avoid hydrogen leaks and friction, with 5 compression stages. The system also includes the cooling system in the high pressure tanks, making it ready to connect to the hydrogen dispenser and work at 350 bar or 700 bar [86].

For simplification purposes, the medium pressure compressor was modelled with the energy consumption required to increase the pressure from 20 bar to 200 bar, estimated at 1 kWh/kg H_2. The technical specifications from Hyet estimate 4 kWh/kg H_2 to reach 1,000 bar [84]. To simplify the model, the efficiency of the compressors was defined constant.

The high pressure stage was assumed to consume 1.5 kWh/kg H_2, considering that the 2.7 kWh/kh H_2 consumption from the IC90 system includes compression from 50 bar to 900 bar and cooling [87]. As a reference, the existing HFS in California, US. have an average energy consumption of 1.67 kWh/kg H_2 for the compression stage [55].

Table 3.3: Technical specifications of the Linde IC90 ionic hydrogen compressor and dispenser [87].

Specification	**Value**
Dimensions (L x W x H)	4.2 x 2.7 x 2.6 m
Electrical requirements – system	105 kW
Inlet pressure	5-200 bar
Approx. throughput single line (maximum)	33.6 kg/h
Approx. throughput double line (maximum)	67.2 kg/h
Maximum operating pressure	1000 bar
Target fueling pressure	700 bar @ 15°C
Ambient operating temperature	-40 °C to 50 °C
Energy requirement at 70 MPa	2.7 kWh/kgH_2

The cost of these systems vary according to the maximum working pressures and hydrogen flows. For the medium pressure compressors, a CAPEX of 420 €/kgH_2/hour was used [80, 88]. The CAPEX for the high pressure compressor was estimated at 4,750 €/kgH_2/hour [88]. The OPEX for both compressors was defined at 4% [52, 88]. These costs were taken from literature as costs show a great variation from compressed natural gas compressors, and project costs depend on the order size to reach reductions due to economies of scale [52, 80].

3.4.5. LOW AND HIGH PRESSURE HYDROGEN STORAGE

The low volumetric energy density of hydrogen is one of the main issues to store it in medium and large quantities. Common storage methods are compressed tanks made from steel with reinforcements from composite materials (e.g. carbon fiber, fiberglass), liquefied hydrogen tanks that operate at very low temperatues (e.g. 20 K), and metal hydrides [89–91]. Compressed hydrogen tanks were selected for the proposed system because of the scale, market readiness, and how they help to simply the system [52, 89, 91]. Liquefied hydrogen required additional equipment and energy to reach the low temperatures, while also having boil off losses [89, 91]. Metal hydrides aren't suited for large hydrogen quantities and also have slow delivery methods [89].

The capacity of the medium storage tank was defined to the peak daily demand, and then rounded up to 1,000 kgH_2. This was done to reduce the probability of the HFS to run out of hydrogen, avoiding to purchase hydrogen from external sources. Stationary steel tanks for hydrogen have been used for years at medium pressures of 150-200 bar [92]. The CAPEX at this pressure range was defined at 600 €/kgH_2 [92] with 1% for the annual OPEX [52].

High pressure hydrogen storage tanks have a smaller capacity, as they are only used when dispensing.

These tanks were set to 70 kgH_2 based on the Linde IC90 datasheet [87], with a CAPEX of 1,100 €/kgH_2 and 1% of OPEX [52].

3.4.6. HYDROGEN TRANSPORTATION

Tube trailers are the most cost efficient hydrogen transportation method for medium size demand sites [93]. As of 2018, composite tube trailer are able to transport up to 875 kgH_2 at 500 bar [93, 94]. Reaching higher pressures causes the cost per transported kilogram to increase significantly. These tanks can achieve up 95% efficiency, with a gravimetric density of 4.6%wt. The main cost factor is the composite materials used to reduce the weight and improve the pressure resistance of the tanks, making the financial viability tied the composite material market. As a reference, the technical specifications of the Titan XL hydrogen tube trailer manufactured by Hexagon Lincoln are shown in Table 3.4.

The proposed HFS uses a tube trailer to buy and sell hydrogen from an external supplier. When there is not enough wind electricity and grid connection for the electrolyzer, it will be necessary to buy hydrogen from an external source. Also, when there is an over production of hydrogen, this can be sold to the market for additional profit. Estimates for hydrogen transportation using tube trailer are within 2 €/kgH_2 for the near future [95].

The expected cost for the tube trailer was set to 730 €/kgH_2 [52, 92], with 2% for OPEX [52]. Additionally, a truck was included in the costs, as well as the driver costs. The CAPEX for the truck was set to €160,000, with 12% of OPEX. Each trip for buying or selling hydrogen was assumed to take 2 hours, with 35 €/hour of labour costs [52].

Table 3.4: Technical specifications of the Titan XL tube trailer [94].

Specification	**Value**
Hydraulic capacity	49,250 liters
Net weight container	19,280 [kg]
Gas weight H_2 (D=0.084 kg/m3)	885 [kg]
Total container weight + H_2	20,165 [kg]
Quantity of cylinders	12
Operating pressure (15 °C)	25 (250) [MPa (bar)]
Burst pressure (min.)	60 (600) [MPa (bar)]
Cylinder type	Type IV
Cylinder design	All-carbon

3.4.7. HYDROGEN DISPENSER AND CHILLER

The tanks inside the fuel cell cars are filled by pressure difference, and the expansion of the hydrogen heats it as it enters the empty tanks in the vehicle, so for safety reasons a chiller is needed to maintain the hydrogen at -40 °C so it does not exceed 80 °C inside the vehicle's tanks[96]. The energy consumption for the cooling system is already implemented in the IC90 system by Linde mentioned in Section 3.4.4.

Due to these technical requirements, hydrogen dispenser are up to 4 times more expensive than the more common CNG compressors [96]. The maximum hydrogen dispensed per hour is 77.16 kgH_2, resultig on a CAPEX for each dispenser of €91,810 /unit (at approximately €2,350 kgH_2/hour with a dispensing capacity of 0.65 kgH_2/min) and 1% OPEX [52]. The 0.65 kgH_2/hour capacity converts to 39 kgH_2/hour, in between the capacity of the single and double line connection of the Linde IC90 dispenser (Table 3.3), indicating the need for 4 dispensers for meet the 77.16 kgH_2/hour peak demand and multiple users This also requires 4 high pressure compressors, high pressure storage tanks, and chillers. The assumed OPEX could be underestimated, as most of the failures in HFS failures up to 2017 were from dispensers and chillers due to more continuous use [27].

The chiller is linked to the dispenser, and therefore is considered within the dispensing system. Only the cooling energy consumption of the IC90 was used, at 0.5 kWh/kgH_2 [87]. This results in the high pressure compressor and the cooling system having a combined consumption of 2 kWh/kgH_2. The CAPEX of the chiller was defined at 2,400 €/kgH_2/hour with 2% of OPEX [52, 96].

3.4.8. SUMMARY OF COMPONENTS

The model components were defined according to the previous sections. All the technical characteristics used in the simulations are summarized in Table 3.5. The economic parameters are defined in table 3.6.

Table 3.5: Summary of the technical parameters and values used in the model simulation process.

Component	Parameter	Values	Units
Wind Turbine	Quantity	1	-
	Rated power	3.5/4.2	MW
	Efficiency	0.95	-
Electrolyzer	Quantity	1	-
	Capacity	15/25/35/45/55	kgH_2/hour
	Efficiency	54.7	kWh/kgH_2
	Water consumption	12	l/kgH_2
Electrolyzer Grid Connection	Capacity	0/0.5/1/1.5/2 2.5/3/3.5/4	MW
Low Pressure Compressor	Quantity	2	-
	Efficiency	1	kWh/kg H_2
High Pressure Compressor	Quantity	4	-
	Efficiency	1.5	kWh/kg H_2
Cooling System and Dispenser	Quantity	4	-
	Efficiency	0.5	kWh/kg H_2
Medium Pressure Storage	Quantity	1	-
	Capacity	1,000	kgH_2
High Pressure Storage	Quantity	4	-
	Capacity	70	kgH_2
Transfers	Import/Export	500	kgH_2

3.5. PERFORMANCE METRICS TO COMPARE SYSTEM CONFIGURATIONS

Performance metrics allow to compare systems in the same terms to assess feasibility regarding each factor. For the proposed system, only reliability, financial and environmental metrics were considered. Other metrics that consider socio-political aspects are also important, but require a deeper analysis of the project location, regarding population, laws and policies [97, 98].

The purpose of these metrics was to recommend a HFS configuration that meets most or all the hydrogen demand, with the highest capacity factors, lowest price for hydrogen, and highest reduction of CO_2 emissions. For example, a small increase in technical performance (reliability and capacity metrics) could be linked to a much higher price for hydrogen (financial metrics), due to the required additional investments.

3.5.1. RELIABILITY AND CAPACITY

Metrics for reliability and technology measure how a system is behaving at a functional level [97]. Being able to meet consumer demand, have the lowest amount of hours out of service or high capacity factors are important to define if a system is feasible or not. The selected reliability and capacity metrics were Loss of Supply Probability (LoSP), Equivalent Loss Factor (ELF), and Capacity Factor (CF). These metrics only consider the hydrogen produced by the electrolyzer, not the hydrogen purchased from external sources. This was done to only evaluate the reliability of the on-site hydrogen generation system. For simplification, all metrics were calculated using yearly values.

LoSP is the ratio between the energy deficit and the total energy demand, in the same period. The LoSP is shown in Equation 3.3. As the LoSP decreases, more demand is being met by the HFS on-site generation system. A low LoSP means less dependency on external hydrogen sources. The Equivalent Loss Factor (ELF) is the ratio between the hours with energy deficit and the operational time period of the system. The ELF is calcualted with Equation 3.4. Both metrics indicate if the HFS configuration is capable to sustain the hydrogen demand, in terms of demand met and down-time [97–100]. The maximum value for LoSP and ELF was defined at 5%, used in renewable energy systems [101]. Also, current HFSs are able to reach a reliability higher than 90% [102]. This value was used to identify systems with high dependence on imported hydrogen.

$$LoSP = \frac{Deficit_{H_2}}{Demand_{H_2}} \cdot 100 \tag{3.3}$$

$$ELF = \frac{HoursDeficit_{H_2}}{8760} \cdot 100 \tag{3.4}$$

The Capacity Factor (CF) is the ratio between the real production of the system and production at rated power, in a year. The CF indicates the utilization factor of a specific equipment o system. In this case, it was used for the wind turbine (Equation 3.5), electrolyzer (Equation 3.6), and grid connection (Equation 3.7). The CF of the grid considers sold and purchased electricity. A high capacity factor is good because it means that the equipment is working closer to the maximum rated capacity, although high utilization may require more maintenance [97].

$$CF_{WindTurbine} = \frac{ElectricityProduction_{Real}}{ElectricityProduction_{RatedPower}} \cdot 100 \tag{3.5}$$

$$CF_{Electrolyzer} = \frac{HydrogenProduction_{Real}}{HydrogenProduction_{RatedPower}} \cdot 100 \tag{3.6}$$

$$CF_{Grid} = \frac{GridUse_{Real}}{GridCapacity_{RatedPower}} \cdot 100 \tag{3.7}$$

3.5.2. FINANCIAL

The Levelized Cost of Hydrogen (LCoH) or Electricity (LCoE) were used to measure the financial performace of the systems. Levelized costs consider capital costs (CAPEX), operation and maintenance (OPEX), the energy sold, and interest rate and inflation for the lifetime of the system [103]. Decommissioning is not included, as these projects are usually re-powered or upgraded when they reach the end of life. The result indicates the suggested price per unit of energy to achieve the indicated interest rate or profit margin. The general formula for LCoE is shown in Equation 3.10, with sold energy as kilograms of hydrogen. Each LCoH phase includes specific components, allowing to understand the share of each phase in the final hydrogen price. The CAPEX and OPEX of all the components used of the LCoH for every phase are detailed in Table 3.6.

To account for inflation (i) and the expected discount rate (v), the real interest was used (Equation 3.8). The discount rate was set to 4%, based on the Weighted Average Cost of Capital (WACC) for renawable energy projects in The Netherlands [104], and the inflation rate to 1.5% based on the inflation average from the last 8 years [68]. The Capital Recovery Factor (CRF)(Equation 3.9) is used to represent future annualized expenses to present value, considering the real interest and lifetime of the project(Equation 3.9). The lifetime of the project was defined at 20 years, limited by the wind turbine lifetime [52].

$$r = \frac{1+i}{1-v} - 1 \tag{3.8}$$

$$CRF = r \cdot \frac{(1+r)^{Years}}{(1+r)^{Years} - 1} \tag{3.9}$$

$$LCoE = \frac{CAPEX \cdot CRF + OPEX}{Energy_{Sold}} \left[\frac{€}{kWh}\right] \tag{3.10}$$

Only the Levelized Cost of Hydrogen for the user (LCoH$_{User}$) was used to select the recommended HFS configuration, as it is the price the consumer is expected to pay at the HFS per kilogram of hydrogen (in €/kgH_2). Different LCoE and LCoH were calculated in the intermediate phases of hydrogen production, according to Figure 3.11. The profit from selling electricity to the grid is considered in this levelized cost as a reduction in the annual OPEX.

The HFS is expected to sell hydrogen in two ways, by dispensing in the HFS, or by selling tube trailers to the industry. Both have a different use of the infrastructure, so shared components like the grid connection were distributed accordingly in each LCoH. Also, as other components (e.g. electrolyzer, low pressure compressor, storage, etc) are used in different proportions by the final user or exports, weighting factors were implemented to distribute the costs in the LCoH of each phase. For example, hydrogen exports rely on the truck and tube trailer (LCoH$_{Trans}$), so a higher portion of this cost is attributed to the final LCoH$_{Exports}$, which is the price per kgH_2 the industry would pay for having hydrogen delivered. The weighting factors for the LCoH$_{Exports}$ and LCoH$_{User}$ are shown in Equations 3.14 and 3.19, respectively.

The LCoE$_{Wind}$ (Equation 3.11) is the cost of electricity per kWh from the wind turbine, assuming a grid capacity the same size as the wind turbine to reach market prices and that all the electricity is sold to the grid. The electrolyzer uses a combination of electricity (LCoE$_{System}$) from the wind turbine and the grid, so this is the price for the electricity used by the electrolyzer. All the other components use electricity from the grid (LCoE$_{Grid}$), as they are connected to the grid for better reliability.

$$LCoE_{Wind} = \underbrace{\frac{(WT + Grid) \cdot CRF}{ElectricityProduction}}_{\text{CAPEX}} + \underbrace{\frac{(WT + Grid)}{ElectricityProduction}}_{\text{OPEX}} \left[\frac{€}{kWh}\right] \tag{3.11}$$

$$LCoE_{System} = \frac{Electricity_{Wind}}{Electricity_{Electrolyzer}} \cdot LCoE_{Wind} + \frac{Electricity_{Grid}}{Electricity_{Electrolyzer}} \cdot LCoE_{Grid} \left[\frac{€}{kgH_2}\right] \tag{3.12}$$

LCoH components for the LCoH$_{User}$ (Equation 3.19) and LCoH$_{Export}$ (Equation 3.18), which are adjusted according to the use of the equipment, are shown in Equations 3.13 to 3.17. These prices indicates the distribution of the total cost per kilogram of hydrogen for all its processing, considering production, low pressure compression, storage, transportation and dispensing.

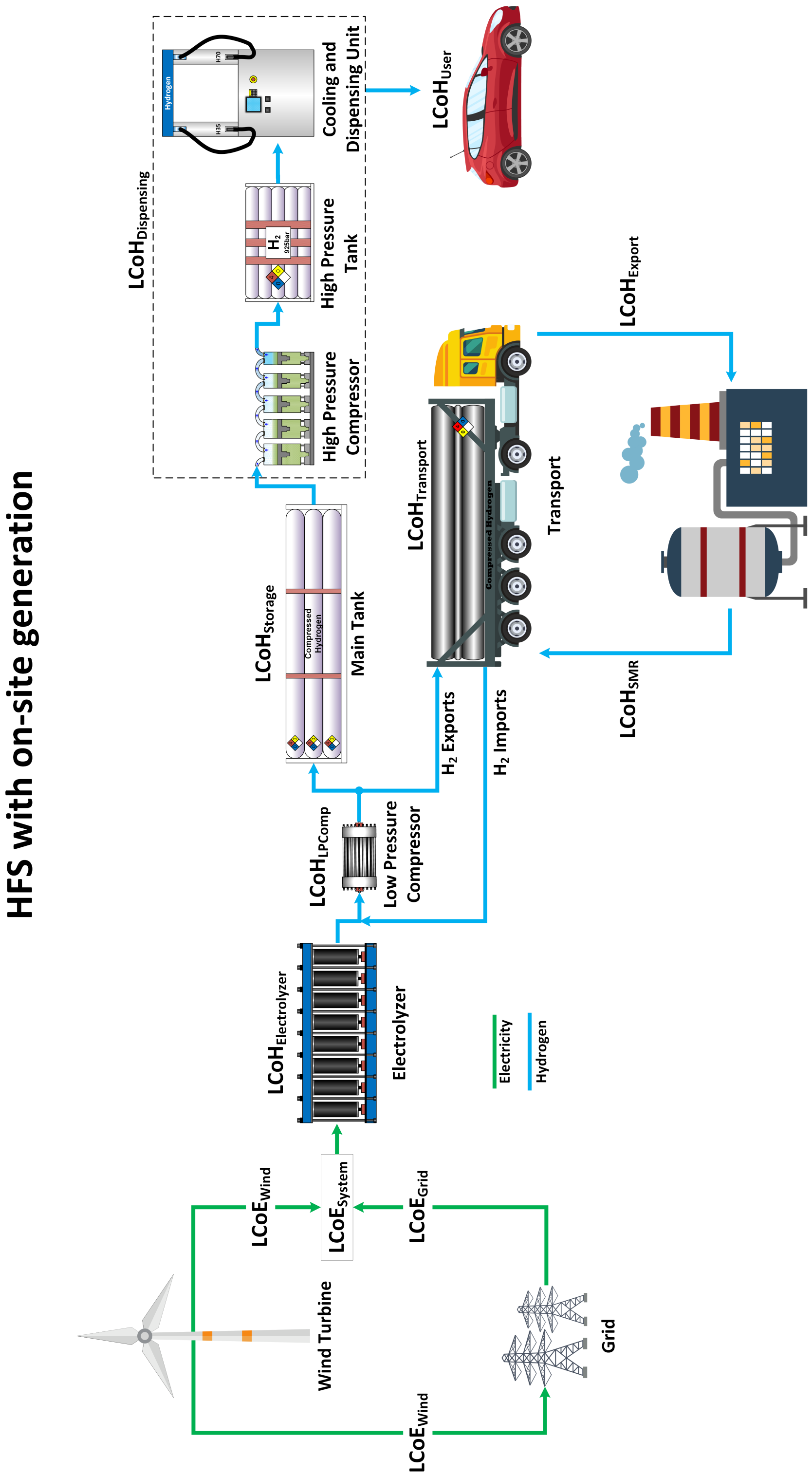


Figure 3.11: HFS model with the distribution of levelized costs of electricity and hydrogen.

$$LCoH_{Elect} = \underbrace{\frac{(Electrolyzer + Grid) \cdot CRF}{HydrogenProduction}}_{\text{CAPEX}} + \underbrace{\frac{(Electrolyzer + Grid + Water + Electricity \cdot LCoE_{System})}{HydrogenProduction}}_{\text{OPEX}} \left[\frac{€}{kgH_2}\right] \tag{3.13}$$

$$LCoH_{LPComp} = \underbrace{\frac{(LPComp + Grid) \cdot CRF}{CompressedHydrogen}}_{\text{CAPEX}} + \underbrace{\frac{(LPComp + Grid + Electricity \cdot LCoE_{Grid})}{CompressedHydrogen}}_{\text{OPEX}} \left[\frac{€}{kgH_2}\right] \tag{3.14}$$

$$LCoH_{Storage} = \underbrace{\frac{(LPTank) \cdot CRF}{StoredHydrogen}}_{\text{CAPEX}} + \underbrace{\frac{LPTank}{StoredHydrogen}}_{\text{OPEX}} \left[\frac{€}{kgH_2}\right] \tag{3.15}$$

$$LCoH_{Trans} = \underbrace{\frac{(Truck + TubeTrailer) \cdot CRF}{TransportedHydrogen}}_{\text{CAPEX}} + \underbrace{\frac{(Truck + TubeTrailer + Operator_{Transfers})}{TransportedHydrogen}}_{\text{OPEX}} \left[\frac{€}{kgH_2}\right] \tag{3.16}$$

$$LCoH_{Disp} = \underbrace{\frac{(HPComp + HPTank + Chiller + Dispenser + Grid) \cdot CRF}{DispensedHydrogen}}_{\text{CAPEX}} + \underbrace{\frac{HPComp + HPTank + Chiller + Dispenser + Grid + Electricity \cdot LCoE_{Grid}}{DispensedHydrogen}}_{\text{OPEX}} \left[\frac{€}{kgH_2}\right] \tag{3.17}$$

The LCoH$_{User}$ (Equation 3.19) and LCoH$_{Export}$ (Equation 3.18) were adjusted according to the share of hydrogen dispensed and exported. Each LCoH component is used in a different proportion depending on the flow through the system. For the LCoH$_{Export}$, the LCoH$_{LPComp}$ share considers that the hydrogen is first stored and then pumped into the tube trailer, requiring using the equipment 2 times. These distributions determine the final price to the used and the industry, including the hydrogen transport to maximize the utilization of the tube trailer.

$$LCoH_{Export} = \frac{H2_{Export}}{H2_{Production}} \cdot LCoH_{Elect} + \frac{2 \cdot H2_{Export}}{H2_{Compressed}} \cdot LCoH_{LPComp} + \frac{H2_{Export}}{H2_{Stored}} \cdot LCoH_{Storage} + \frac{H2_{Export}}{H2_{Transported}} \cdot LCoH_{Trans} \left[\frac{€}{kgH_2}\right] \tag{3.18}$$

$$
\begin{aligned}
LCoH_{User} = & \frac{(H2_{Production} - H2_{Export})}{H2_{Production}} \cdot LCoH_{Elect} + \frac{(H2_{Production} + H2_{Import})}{H2_{Compressed}} \cdot LCoH_{LPComp} \\
& + \frac{(H2_{Production} + H2_{Import})}{H2_{Stored}} \cdot LCoH_{Storage} + \frac{H2_{Import}}{H2_{Transported}} \cdot LCoH_{Trans} \\
& + \frac{(H2_{Import})}{H2_{Disp}} \cdot LCoH_{SMR} + LCoH_{Disp} \left[\frac{€}{kgH_2} \right]
\end{aligned}
\tag{3.19}
$$

Table 3.6: Components of the levelized costs for wind electricity and hydrogen.

Metric	Component	CAPEX	OPEX[1]	LT[2]	References
$LCoE_{Wind}$ [3]	Wind turbine	1,100 €/kW	2.8%	20	[52, 65]
	Grid	HFS dependent[4]	HFS dependent[4]	-	[67]
$LCoH_{Production}$	Electrolyzer	840 €/kW	4%	20[5]	[76]
	Water treatment	1.2 €/l/day	4.8%	25	[105]
	Bought grid electricity	-	$LCoE_{System}$	-	[69]
	Water	€680	0.94 €/m^3	-	[106]
	Bought/Sold H_2	-	3 €/kgH_2	-	[107]
$LCoH^6_{LPComp}$	LP compressor	420 €/kgH_2/hour	4%	10	[52, 80, 88]
	Grid electricity	-	0.047 €/kWh	-	[69]
$LCoH_{Storage}$	LP tanks	600 €/kgH_2	1%	30	[52, 92]
$LCoH_{Transport}$	Truck	€160,000	10%	8	[52]
	Tube Trailer	730 €/kgH_2	2%	30	[52, 92]
	Operator	-	70 €/trip	-	[52]
$LCoH^6_{Dispensing}$	High pressure tanks	1,100 €/kgH_2	1%	30	[52]
	High pressure comp	4,750 €/kgH_2/hour	4%	10	[88]
	Dispenser	2,350 €/kgH_2/hour	1%	10	[52]
	Chiller	2,400 €/kgH_2/hour	2%	15	[52, 96]
	Grid electricity	-	0.047 €/kWh	-	[69]

[1] Annual expenditure, as a percentage of the CAPEX.
[2] Lifetime in years.
[3] Price of the electricity sold, included in LCoH Production.
[4] Grid capacity depends on the HFS configuration.
[5] Stack lifetime of 80,000 hours (Section 3.4.3).
[6] Grid connection costs are included.

Equipment replacement is also considered in the CAPEX calculations for the electrolyzer stack, compressors, truck and other components, considering the lifetimes defined by the manufacturers. The wind turbine, with an estimated lifetime of 20 years, defined the lifetime of the project [52]. Electricity is purchased at grid price and sold at the LCoE of the installed wind turbine. The LCoE of the wind turbine assumes that 100% of the electricity can be sold to the grid, to have a competitive and realistic market price. Hydrogen production includes all the equipment and goods (electricity and water) required, as well as the purchased hydrogen from external sources to meet demand. Compression and storage includes the hydrogen compressors and storage tanks. Transportation only consists of the truck and tube trailer, as well as the operator fees. Finally, the hydrogen dispensing costs include the dispenser and cooling system (chiller). The capacities and prices indicated per hour or per day were calculated with the maximum value. Peak hydrogen consumption is 77

kgH_2, as estimated in Section 3.2.

3.5.3. ENVIRONMENTAL

The main objective of changing from fossil fuels to hydrogen is emissions reduction. Each proposed system achieves a different CO_2 emissions value due to the different components. The emissions linked to each purchased kilogram of hydrogen were also accounted for, assuming it was produced with Steam Methane Reforming (SMR). SMR produces and average of 7 $kgCO_2eq/kgH_2$ [108]. However, this amount only considers production and not transportation to the site.

The Dutch electricity grid produced between 410-550 gCO_2eq/kWh, in 2013 [109, 110]. By 2030, The Netherlands is aiming to reduce carbon emissions by 49% from 1990 quantities, following the Paris Agreement requirements . Dutch emissions from electricity generation in 1990 were estimated at 606 gCO_2eq/kWh [111]. According to the plan to shift out coal plants by 2020 and install large capacity solar photovoltaic and offshore wind [112], emissions from the energy sector in 2030 are estimated at 150 gCO_2eq/kWh [113].

The improvements in wind turbine efficiency and manufacturing show that the lifecycle emissions for electricity produced with onshore wind turbines are in the range of 5-8 gCO_2eq/kWh [114, 115], roughly 50 times cleaner than the current Dutch grid. This means that producing 1 kgH_2 from grid electricity produces approximately 22.4 $kgCO_2eq$, compared to 383 gCO_2eq if produced completely from wind electricity at 7 gCO_2eq/kWh. In 2030, 1 kgH_2 produced directly from the Dutch grid will produce 8.2 $kgCO_2eq$, if the infrastructure is improved as planned.

The comparison between the HFS configurations in the model is made with the expected emissions per kgH_2 produced by the HFS system to meet demand, including electricity and hydrogen trade. Emissions removed from the electric grid were also considered, as the system is selling cleaner electricity to the grid. It was estimated that wind electricity sold to the grid removes approximately 143 gCO_2eq/kWh. Equation 3.20 was used with the yearly values of emissions.

$$Emissions_{CO_2eq/kgH_2} = \frac{Emissions_{Wind} + Emissions_{Grid} + Emissions_{HydrogenbySMR}}{Hydrogen_{Production}} \tag{3.20}$$

From the data currently available, producing hydrogen with grid electricity pollutes more than SMR, assuming the average gCO_2eq/kWh from the Dutch electric grid. The use of wind power to generate hydrogen directly via electrolysis is highly recommended, although in other countries the use of the electric grid may also be suitable to reduce emissions. Assuming a consumption of 54 kWh/kgH_2, a country with an electric grid producing less than 130 gCO_2eq/kWh would have a hydrogen production with lower emissions than with SMR. From the environmental perspective, this would make attractive hydrogen production directly from the electric grid.

Countries like Norway, Sweden, Uruguay, and Costa Rica, with renewable electricity production close to 100%, can produce electricity at 50 gCO_2eq/kWh or less [116]. These electric grids would produce 2.7 $kgCO_2eq/kgH_2$ when using grid powered electrolysis. FCEV emissions would produce 27 gCO_2eq/km (assuming current FCEV efficiency of 1 $kgH_2/100km$), less than a third of Dutch vehicle emissions in 2018. These type of specific country studies are necessary to decide on the most appropriate system for each on of them.

Modern electric vehicles have an estimated efficiency of 14-20 kWh/100km [117]. EV efficiency fluctuates according to the size, weight, aerodynamics, and power system of the vehicle. An EV with an efficiency of 17 kWh/100km results in 69.7 gCO_2eq/km if the electricity is produced by the Dutch electric grid.

These results indicate that it is necessary to compare both technologies, including the energy supply, to decide on a greener transition path. As the power and energy demand increases, the battery size and weight with current technology increases to a technically infeasible point. FCEVs provide a better alternative as the energy requirements increase, as with large trucks, buses and medium-sized vehicles.

According to the European Environment Agency, in 2016 The Netherlands had one of the lowest average passenger car CO_2 emissions in Europe, with 106 gCO_2/km, and 5.7% of the vehicle fleet produced less than 50 gCO_2/km [25]. The Hydrogen Council estimates an reduction of 11% in emissions from ICE vehicles in 2030, lowering it 94.34 CO_2/km. These estimations are still too high to meet the necessary emission goals for the near future.

3.6. SUMMARY

This Chapter described how the hydrogen demand for a HFS in The Netherlands was calculated, based on fuel consumption patterns. The proposed model was defined, including the wind pattern for the location and the components used in each HFS configuration. A comparison method was defined using metrics to evaluate the performance of all the HFS configurations. This was defined to recommend a configuration that meets objectives of low hydrogen price, high reliability, and low CO_2 emission.

The hourly hydrogen demand for The Netherlands was created for one complete year. This considered daily, weekly, and seasonal fluctuations. The generated hydrogen demand assumes that users of the HFS will be able to drive the same amount of kilometers per year as the amount provided by a fossil fuel fueling station.

Market ready technology was investigated to select the most appropriate components for the proposed HFS. Efficiencies and economical factors were estimated to 2030, based on literature and improvement trends over the years.

The different components allowed to simulate 90 HFS configurations. The results from the simulations are detailed in Chapter 4. The recommended HFS configuration is analysed further in Chapter 5. The latter included the economic distributions of the system costs and its impact if implemented at a national scale, based on the GIS study from Chapter 2.

4

Evaluation of the proposed HFS configurations

Which HFS configuration is best suited for the conditions a case study in Zoetermeer?

This Chapter evaluates the results of the model proposed in Section 3.3, based on the performance metrics defined in Section 3.5. A recommended configuration was selected using a simple methodology to eliminate the systems with low performance. The selection criteria is defined in the following section.

Similar to the filtering process used in Chapter 2, each selection step eliminated the non-compliant HFS configurations. This simplified the presentation of the results. The complete plots of the simulations are shown in Annex C.

4.1. Selection methodology for HFS configurations

The selection method was defined by giving different priorities to the metrics. As one of the main objectives of the hydrogen economy is to lower emissions from the transportation sector, environmental metrics were given the first priority. First, the main condition was that the average emissions from the HFSs have to be equal or less than 2.8 kgCO_2eq/kgH_2. This stems from the calculated emissions of EVs powered from the grid, assuming an efficiency of 15 kWh/100km. Second, the HFS has to comply with the reliability metrics of LoSP and ELF at less than 5%, as defined in the Section 3.5.1, based on current state-of-the-art HFS with reliability higher than 90% [102]. Finally, the remaining systems were compared with the $LCoH_{User}$, as this is the price at the dispenser for the user. HFS configurations that complied with the previous requirements and had similar $LCoH_{User}$ were compared to select the system with the best cost-benefit indications. The steps of the selection methodology are shown in Figure 4.1.

Other technical metrics like capacity factors were not used for the selection process. Those metrics were used for the analysis of the recommended system and to verify the model.

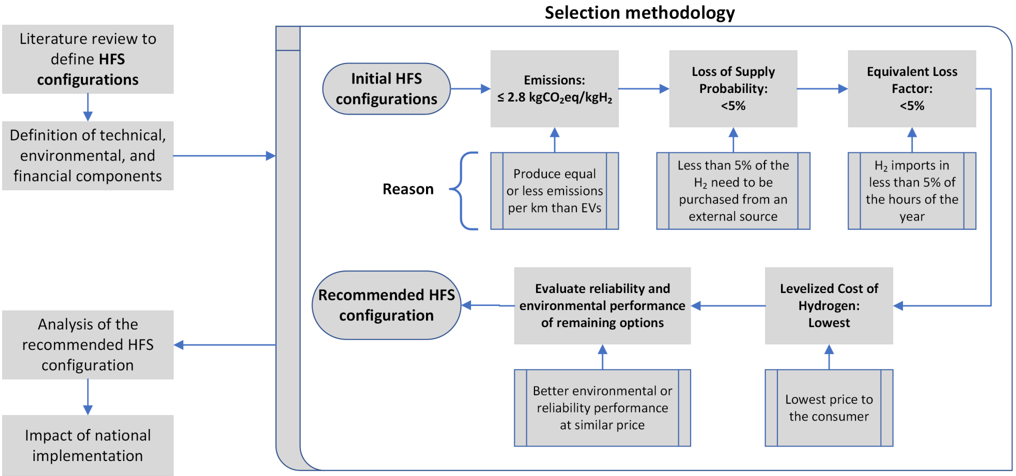


Figure 4.1: Selection method for the recommended HFS configuration, based on the metrics proposed in section3.5.

4.2. ENVIRONMENTAL RESULTS

The first selection step was based on the emissions caused by the HFS. The emissions considered were the ones produced by the used grid electricity and purchased hydrogen (with SMR as the assumed production method). The calculation also considered the emissions removed from the grid by selling wind electricity. Each kWh of wind energy sold to the grid removes around 143 gCO_2eq, according to the data in Section 3.5.3. Additional emissions from hydrogen transportation, vehicle emissions, etc. were neglected as they are not directly linked to the hydrogen production process.

In Figure 4.2, the equivalent emissions per kg of hydrogen are shown for all the configurations. Each box includes all the capacities of the electrolyzer grid connection, from 0 MW to 4 MW. It can be seen that the higher the power capacity of the electrolyzer, the higher the grid electricity consumption to produce hydrogen. This is because the model is focused on maximum hydrogen production.

The increase in wind turbine capacity does result in emission reductions. On average, emissions are reduced by 500 gCO_2eq/kgH_2 with the increase of the wind turbine capacity from 3.5 MW to 4.2 MW. For the configurations with a grid connection of 0 MW, the improvement varies between 1% and 11% for the lowest and highest electrolyzer capacities, respectively. This is because more hydrogen is produced with wind electricity. Detailed results are shown in the Annex C, in Figures C.1 and C.2 for both wind turbine capacities.

At higher grid connections and low electrolyzer capacities, low emissions can be achieved by the selling clean electricity to the grid. The configurations with a lower electrolyzer capacities have a lower electricity consumption and more hydrogen purchases, which are linked to a high amount of CO_2 emissions. From these configurations, the ones with higher grid capacity are able to sell more wind electricity to the grid, thus reducing emissions. The high dependence on imported SMR hydrogen from the systems with smaller electrolyzer capacities make them non-viable from an environmental perspective.

The electrolyzers with large capacities, 45 and 55 kgH_2/h, are able to produce more hydrogen, but require more electricity from the grid which increases emissions. However, those are still lower than imported SMR hydrogen. From the oversized systems, only the HFS configuration with a 4.2 MW wind turbine, 1 MW grid capacity and a 45 kgH_2/h electrolyzer complied with the emission limits.

Oversized systems make environmental sense with clean grid electricity. If the electric grid emissions are too high, there is a reduction in the environmental benefits of the change from fossil fuels to hydrogen transportation. However, by 2030, grid emissions in The Netherlands should be lower.

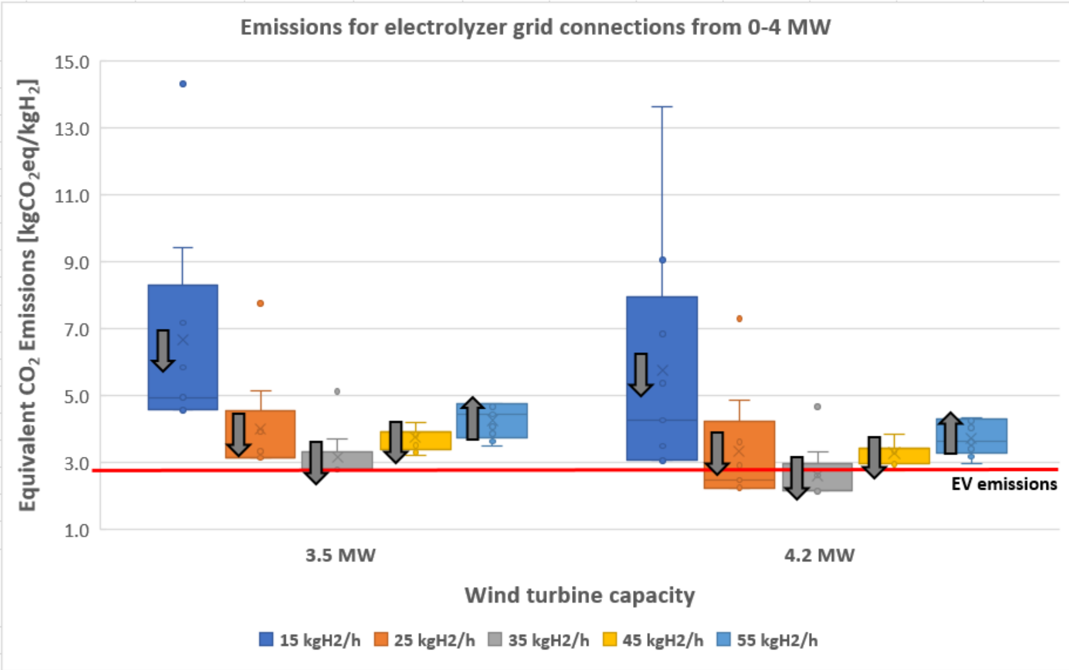


Figure 4.2: Emissions results of the HFS systems. The gray arrow indicates the electrolyzer grid capacity from 0 MW to 4 MW (increasing capacity).

4.3. RELIABILITY RESULTS

The HFS configurations that complied with the emissions limit were filtered by reliability. The LoSP and ELF limits were defined at a maximum of 5% in Section 3.5.1. Respectively, these metrics evaluate the unfulfilled hydrogen demand and the amount of hours that required hydrogen imports from external sources. The LoSP for both wind turbines with capacities of 3.5 MW and 4.2 MW, are shown in Figure 4.3, respectively.

In this Section, it is important to highlight that the electrolyzer was set to produced hydrogen between 10-100% of its rated capacity, according to the available electricity. This limits the reliability of the systems without grid connection, as not all the wind electricity is used for hydrogen production. Low grid connections and higher capacity electrolyzers are more dependent on external hydrogen production. For instance, the 45 and 55 kgH_2/h electrolyzers, with more than 1.5 MW of grid connection, can achieve almost 0% of LoSP. However, these configurations were eliminated due to high emissions in the previous step.

Figure 4.3 shows that the HFS configurations with the 35 kgH_2/h electrolyzer are the only capable of an LoSP lower than 5% with a grid capacity of 1.5 MW or higher. The only oversized system, with the 45 kgH_2/h electrolyzer. The systems with a small electrolyzer capacity or low grid capacity, cannot meet the total annual hydrogen demand, resulting in high LoSP.

The ELF results showed to be lower than 5% for all the proposed HFS configurations. The highest ELF was of 4.5%, for a total of 398 hours with low hydrogen storage (less than 10% of the storage tank). Each hour without hydrogen means 1 hydrogen truck trailer delivered to the HFS for a 500 kgH_2 transfer. Hydrogen bought from an external source was assumed to be available within 1 hour, as hydrogen becomes more accessible in the near future.

In a future with more developed hydrogen infrastructure, large quantities of hydrogen will be available for purchase, including easier access to hydrogen pipelines. Hydrogen pipelines are within the vision for a hydrogen economy [1], as they would remove the concerns about hydrogen supply from the on-site hydrogen generation system.

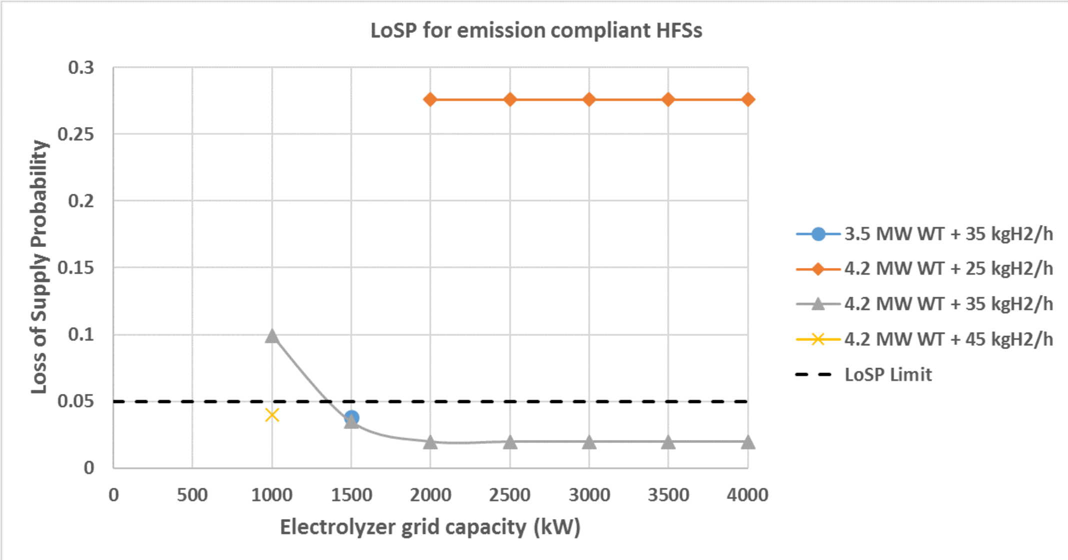


Figure 4.3: LoSP results of the HFS systems with a 3.5 MW and 4.2 MW wind turbines, with electrolyzer grid capacities between 0-4 MW.

The minimum reliability limits discarded the HFSs with electrolyzers of 25 kgH_2/h. Only the HFS configurations with the 35 and 45 kgH_2/h electrolyzer remained, with specific grid capacities between 1 MW and 4 MW, were suitable for the financial filter.

4.4. FINANCIAL RESULTS

After the emissions and reliability filters, the HFS configurations were compared with the $LCoH_{User}$. The results are shown in Figure 4.4 for the electrolyzers with a capacity of 35 and 45 kgH_2/h and electrolyzer grid capacities between 1-4 MW. $LCoH_{User}$ is stable for this system in the siltered grid capacities. Higher grid capacities require higher CAPEX and OPEX, but mean a higher hydrogen production. Electricity transport costs have a small influence at high electricity consumption.

The price difference between the HFS configurations is mainly related to the additional revenue from sold electricity. As these systems comply with the minimum reliability minimum, hydrogen imports don't have a significant impact on the $LCoH_{User}$.

Results show that the HFS configuration with 45 kgH_2/h electrolyzer, 1 MW grid connection and a 4.2 MW wind turbine has the lowest $LCoH_{User}$. The $LCoH_{User}$ resulted in 5.034 €/kgH_2, for the year 2030. As there were no HFS configurations with a similar cost to the user, the last selection step was not necessary.

The imported hydrogen has a similar price (assumed at €3/kgH_2 by 2030 [107]) than hydrogen produced completely with grid electricity (approx. €2.75/kgH_2, with the extrapolated electricity cost in 2030). However, the model considers that the truck and tube trailer from the HFS will transfer the imported hydrogen, meaning that the consumer pays for the additional hydrogen transportation costs.

Regarding the LCoH of hydrogen production, none of the HFS systems resulted in a cost lower than SMR hydrogen production. However, there are important differences in emissions. If a carbon tax is implemented in the future, the economic feasibility of these systems would be improved.

Taxes or subsidies were not included in the calculations due to their variability in budget over the years. The Netherlands has multiple options to promote clean energy production, like the Renewable Energy Production Incentive Scheme (SDE+), with the benefits varying according to installed capacity and environmental improvements [13].

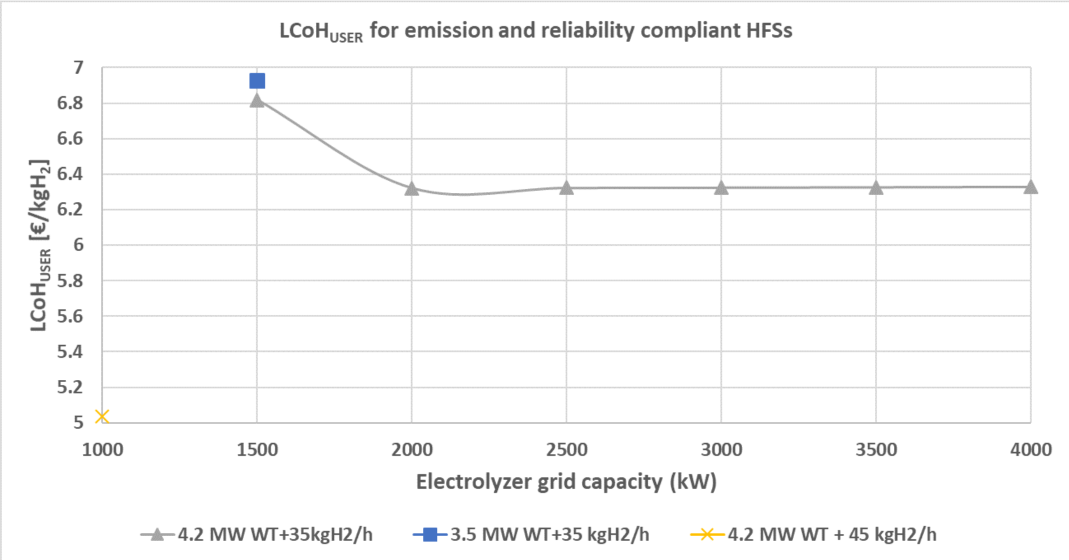


Figure 4.4: $LCoH_{User}$ results for the HFS configurations that comply with the environmental and reliability limits.

4.5. RECOMMENDED HFS CONFIGURATION

The selection methodology indicated that the HFS configuration with an electrolyzer of 45 kgH_2/h capacity, a 4.2 MW wind turbine, and 1 MW grid connection for the electrolyzer was compliant with the defined minimum performance metrics and the lowest $LCoH_{User}$. The main characteristics are detailed in Table 4.1.

Table 4.1: Main simulation results of the HFS configuration obtained with the selection methodology.

Parameter	Selected HFS
Wind turbine [MW]	4.2
Electrolyzer [kgH_2/hour(MW)]	45 (2.4)
Grid connection [MW]	1
Emissions [$kgCO_2eq/kgH_2$]	2.75
LoSP[1] [%]	3.97
ELF[1] [%]	0.274
$LCoH_{User}$ [€/kgH_2]	5.034
$LCoH_{Export}$ [€/kgH_2]	1.639
CAPEX [€M]	13.2
OPEX [€M]	1.40
H_2 Imports [kgH_2]	12,000
H_2 Exports [kgH_2]	37,000

[1] Lower values indicate better reliability.

4.6. SUMMARY

This Chapter evaluated the proposed HFS configurations defined in Section 3.4.8, according to the defined performance metrics. The HFS configuration with a 45 kgH_2/h electrolyzer, a 4.2 MW wind turbine, and a 1 MW grid connection for the electrolyzer was selected. This HFS setup has a reliability of more than 96%, in terms of meeting hydrogen demand. Also, it has lower emissions per kilogram of hydrogen than common industrial hydrogen production processes, with an estimate of 2.75 $kgCO_2eq/kgH_2$. For the FCEVs fueled by this HFS, emissions per kilometer are lower than EVs charged with the Dutch grid in 2030. The use of a wind turbine with a larger capacity means lower emissions and higher reliability without a significant increase in LCoH.

The initial investment required for the complete system, including the hydrogen tube trailer and truck for hydrogen transfers, resulted in €13.2M. In 2017, the CAPEX for HFSs in USA, with on-site electrolysis, was between $25k-$45k per kgH_2/day [27]. Using these values, a HFS with a capacity of 1,080 kgH_2/day, like the one proposed, would mean a total CAPEX between $27-$48M. As the components and technical specifications of these reference HFSs are not known, the comparison only indicates that the proposed HFS offers a competitive option for hydrogen production and distribution.

The effect of the grid capacity in every configuration had an impact both in cost and reliability. Higher grid capacities mean lower LoSP if the electrolyzer is capable of meeting the demand. However, the grid costs for CAPEX and OPEX increase considerable with the installed capacity. This reduced the financial feasibility of the system.

Also, higher dependence on grid electricity meant higher emissions related to hydrogen production. This is because the grid electricity in The Netherlands, as of 2017, will still rely on fossil fuels by 2030, although with a higher percentage of renewable energy. In the scenarios with high electricity consumption produced, SMR is more sustainable than using an electrolyzer for hydrogen production.

The approach used in this Chapter aimed to meet specific technical considerations, but other approaches can be implemented according to the availability of cheaper electricity, low emission hydrogen, and availability of hydrogen at large scale, to name a few.

Chapter 5 develops on the specifics of the recommended HFS configurations. In this Chapter, the technical and financial components are analysed, as well as the possible impact of this system if implemented at a national scale in The Netherlands.

5
ANALYSIS OF THE RECOMMENDED HFS CONFIGURATION

How does the HFS perform as a single system and scaled to a national scale in The Netherlands?

Following the selection process carried out in Chapter 4, the specific technical and economic results of the recommended system are detailed in this Chapter. The main components of the recommended HFS, based on the wind profile of Zoetermeer and the expected hydrogen demand in The Netherlands in 2030, are:

- One 4.2 MW wind turbine,
- One PEM electrolyzer with a rated capacity of 45 kgH_2/h (2.4 MW),
- A grid capacity of 1 MW for the wind turbine and electrolyzer,
- One 1,000 kgH_2 medium pressure storage tank,
- Four hydrogen dispensers at 700 bar, and
- One hydrogen tube trailer with a capacity of 500 kgH_2.

With the statistics of this HFS, the impact of a national implementation was calculated based on the results of the GIS study performed in Chapter 2.

5.1. TECHNICAL ASPECTS

The HFS runs entirely on electricity, either from the wind turbine or the grid. Utilities, such as the low and high pressure compressors or the cooling system, are powered directly by the grid. Figure 5.1 shows the source of the electricity used for hydrogen production, with 65% of the electricity used by the complete HFS from the wind turbine (12.25 GWh). From the remaining wind energy, not used directly by the electrolyzer, 1.61 GWh/year is sold to the grid and only 250 MWh or electricity per year is curtailed.

However, as not all the electricity is used for hydrogen production, the source of the hydrogen has a different distribution. Based on the hydrogen production of 335.37 tH_2, hydrogen produced directly with wind electricity accounts for 68% of the demand. The rest is produced with grid electricity in times with low wind speeds, and 13 tH_2 are imported to support demand in the cases of high demand. The hydrogen used to fill the tanks at the beginning of the year (1 tH_2) is also included.

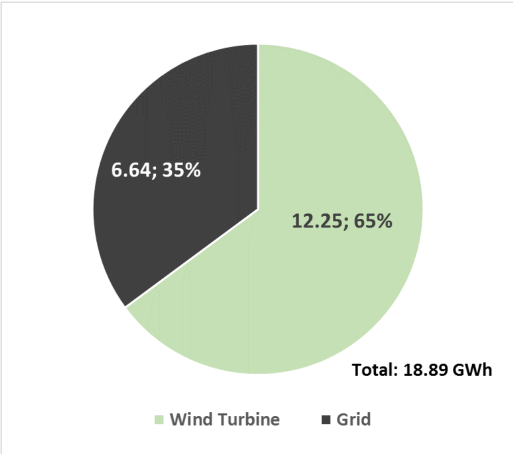


Figure 5.1: Electricity sources for hydrogen production, per year.

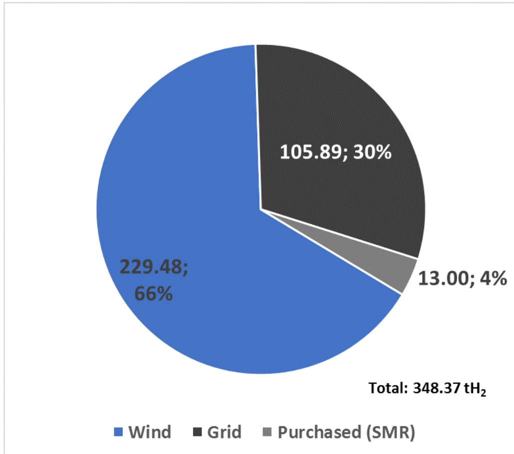


Figure 5.2: Hydrogen sources used by the HFS, per year.

Regarding capacity factors, the electrolyzer, with a higher capacity than the average hourly hydrogen demand, reached a capacity factor of 83.05%, represented in load duration curve in Figure 5.3. The HFSs in USA have a maintenance time of 5 hours/quarter for the electrolyzer, and an average HFS maintenance of 360 hours/year (96% of availability) [27]. This indicates that current technology is already achieving high capacity factors. The grid capacity is 40% of the electrolyzer rated power, meaning that the generation profile does depend on the electricity production from the wind turbine. With a total electricity consumption of 18.89 GWh and an on-site production of 335.37 tH_2, the resulting consumption of the complete system is 56.4 kWh/kgH_2 (including the compression of imported hydrogen).

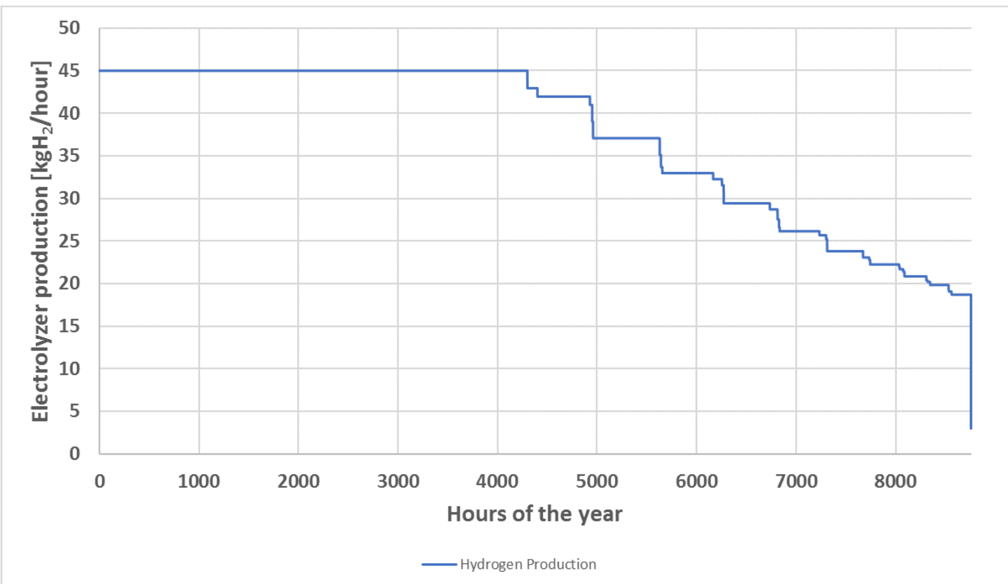


Figure 5.3: Load duration curve for the 45 kgH_2/hour (2.4 MW) electrolyzer.

If additional maintenance time is required, it could be addressed with additional hydrogen imports to satisfy demand and allow to service the equipment. As for the grid, the capacity factor reached a 40.08%. This indicates that the grid capacity may be over-sized, but it allows to reduce the curtailed electricity by being utilized at more than 50% of the 1 MW capacity for 1,632 hours/year.

The wind turbine capacity factor is 39.24%, with only 194 hours per year with no electricity production, about 2.2% of the year. As maintenance needs to be planned, maintenance has to be scheduled and hydrogen imports programmed. Maintenance for the electrolyzer and wind turbine should be carried out at the same time to reduce total plant downtime. The HFSs monitored by NREL have an average downtime of 15 days per year [27], which could be reduced by the near future as hydrogen technology matures. The control of downtime for maintenance was not considered within the model.

5.1.1. HYDROGEN IMPORTS AND EXPORTS

The HFS imports and exports hydrogen according to the level of the low pressure tank. Figure 5.4 shows the amount of tube trailers used for imports and exports per month, each one of 500 kg H_2. The dependency on hydrogen imports correlates to the demand increase during the summer months, as described in Section 3.2. Also, the average wind profile in Zoetermeer showed higher wind speeds during winter months than in summer months, opposite to the demand.

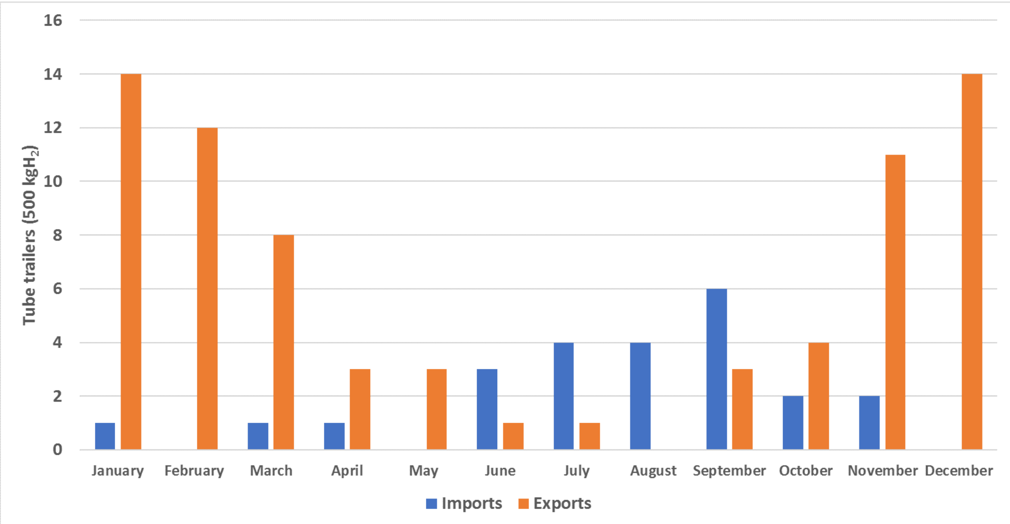


Figure 5.4: Yearly hydrogen imports and exports per month. Each hydrogen transfer means 500 kgH_2 transported via tube trailer.

The tube trailer is used only 98 times during the entire year. This indicates each HFS having their own truck and tube trailer is a waste of resources. Different HFS within certain proximity could use the same truck and tube trailer, and share the CAPEX and OPEX, leading to a lower LCoH for the consumer. Also, the HFS could rely on the truck and tube trailer from an external supplier, only paying for the service when needed and removing this components from the CAPEX and OPEX.

5.2. ECONOMIC ASPECTS

One of the main aspects for the success of these type of projects is the financial feasibility. The distribution of the CAPEX helps to identify which components lead to the higher expenditure. The main components, as seen in Figure 5.5, are the wind turbine and the electrolyzer, adding to 53.9% of the total CAPEX. The grid connection only accounts for 2.1% of the CAPEX, as it is only 1 MW. This indicates that small grid capacities can have a positive impact in the HFS reliability while not leading to an important increase in the initial investment.

Also, as mentioned in the previous section, the truck and tube trailer are used only 98 days in the year, and are responsible for 5.8% of the CAPEX. This could be eliminated by renting the equipment from an external company, leading only to OPEX costs.

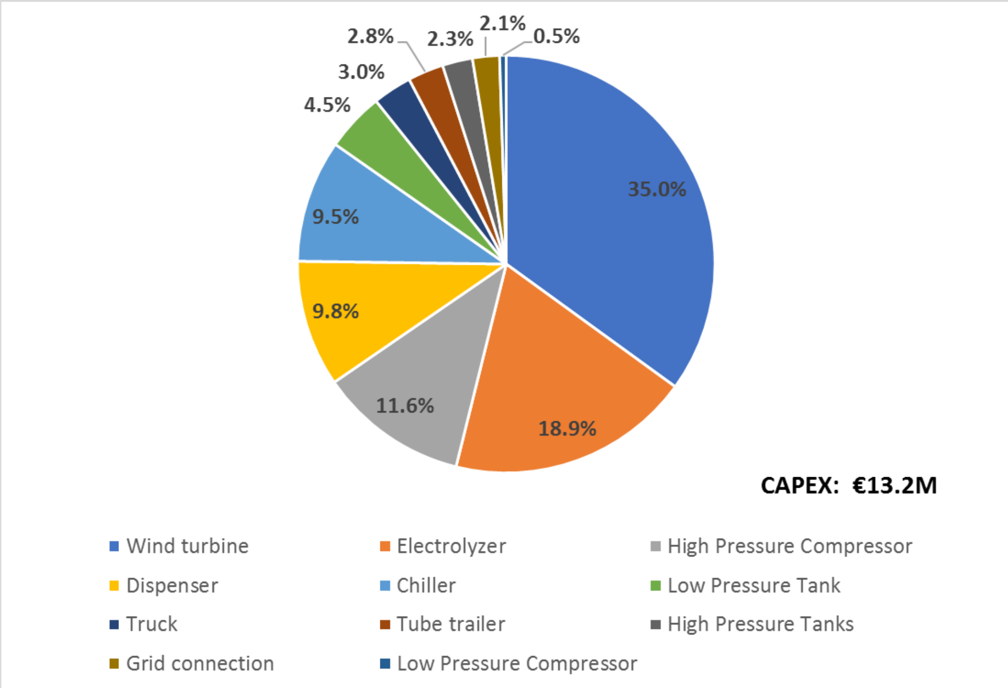


Figure 5.5: Breakdown of the CAPEX for the recommended HFS configuration.

The OPEX, shown in Table 5.1 was divided according to the LCoH. These six components account for 85% of the annual expenditure in operation and maintenance. Electricity costs were allocated based on consumption, and grid connection costs based on grid capacity per component. The $LCoE_{Wind}$ includes the costs related to the grid connection for the electrolyzer. In this case, contrary to the CAPEX, the grid costs are the main part of the OPEX. The calculations for the grid maintenance were based on the cost tables published by Stedin [67]. These costs could vary due to the impact of electricity transport costs, which could be different with a different contract with Stedin or respective DSO.

Hydrogen imports, assuming €3/kgH_2 [107], were included in the final $LCoH_{User}$ for the purchase of 13 tH_2. As the system has high reliability and is therefore almost self-sufficient, hydrogen imports don't have a important influence on the $LCoH_{User}$ (2.1%). Water is only 0.26% of the OPEX, at 3,928 m^3/year. Because the cost of the water connection and pipe water is negligible, rain water collection systems would produce extra costs because of additional maintenance and new components (tanks, pumps, piping, control system, etc.), so they are not recommended.

The results for the LCoH of every phase, according to Equations 3.13-3.17, are shown in Table 5.2. These costs are distributed according to the equipment use for the final $LCoH_{User}$ and $LCoH_{Export}$. If the costs were only allocated to the final HFS user, the $LCoH_{User}$ would be 6.557 €/kgH_2. The highest costs are production, transportation and dispensing, as these phases require the most expensive equipment.

Finally, the distribution of the $LCoH_{User}$ is shown in Figure 5.6. The cost of production is the driver of the cost of hydrogen. Considering peak use, the four dispensing systems increase the costs up to 25% of the

Table 5.1: Annual OPEX for each component of the HFS, classified by LCoH category.

Cost	Component	Cost [k€]	% Per component	% Per LCoH category
$LCoE_{Wind}$	Grid connection	130.36	50.24	18.61
	Wind turbine	129.36	49.76	
$LCoH_{Production}$	Electricity	901.94	91.44	70.61
	Electrolyzer	80.74	8.19	
	Water	3.69	0.37	
$LCoH_{LPCompression}$	Electricity	17.99	81.70	1.58
	Grid connection	2.52	11.44	
	LP compressor	1.51	6.87	
$LCoH_{Storage}$	LP Tank	6.00	100	0.43
$LCoH_{Transport}$	Truck	16.00	53.05	2.16
	Tube Trailer	7.30	24.20	
	H_2 Transport	6.86	22.75	
$LCoH_{Dispensing}$	HP compressor	34.20	37.05	6.61
	Electricity	28.92	31.32	
	Chiller	14.82	16.05	
	Dispenser	7.25	7.86	
	Grid connection	4.05	4.39	
	HP tanks	3.08	3.34	
	Total	1,396.83		100.0

Table 5.2: Complete LCoH of each HFS phase.

LCoH	Cost [€/kgH_2]
Production	3.501
LP Compression	0.076
Storage	0.118
Transport	1.614
Dispensing	1.248

cost to the user. As compression becomes more efficient, the allocated costs to this cost components are lower and may reduce the technical requirements of HFSs without production infrastructure. In this case, the HFS is almost at the same hydrogen production cost as SMR. For 2020 onwards, an $LCoH_{User}$ between €4-6/kgH_2 is within the expected for state-of-the-art electrolyzers and low cost electricity, specially with high electrolyzer capacity factors [118].

Disregarding emissions, a HFS with a lower $LCoH_{User}$ would probably be one without the on-site hydrogen production, taking all the hydrogen from a hydrogen gas grid. This would be the ideal case if the hydrogen available at large scale is produced by renewable energy.

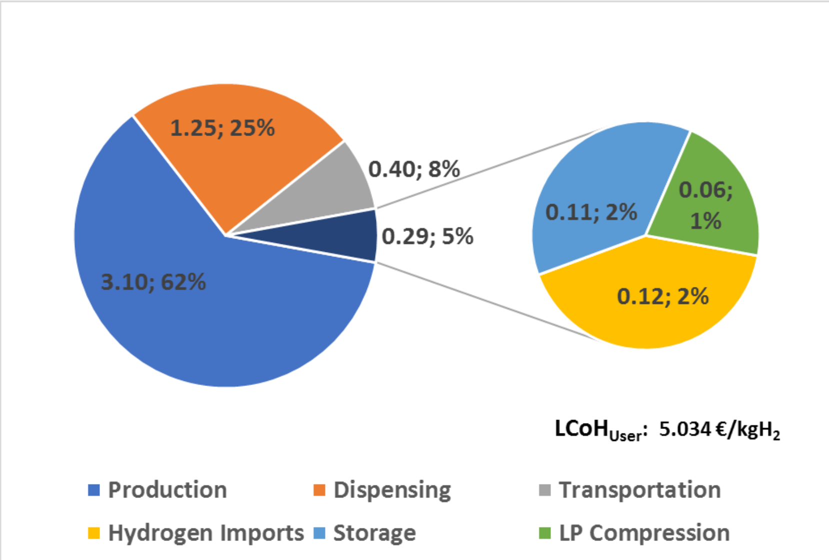


Figure 5.6: Breakdown of the $LCoH_{User}$ for the recommended HFS configuration.

The $LCoH_{User}$ breakdown indicates that hydrogen production (electrolyzer) and dispensing (high pressure compressors, chillers, and dispensers) have the highest share of the cost. The components required for these phases are the most expensive and O&M intensive. The system has a reliability higher than 96%, meaning that hydrogen imports don't have a big impact on the final price for the consumer. However, as the truck and tube trailer are under utilized, with only 98 trips per year, transportation costs are 8% of the price for the consumer. The low price and electricity consumption of the low pressure compressors are key to lower the price to the consumer, representing only 1% of the LCoH.

The $LCoH_{Export}$ resulted in 1.639 €/kgH_2, where the main cost driver is the hydrogen transportation (74%). The remaining 24% is allocated to hydrogen production and 1% to hydrogen compression and storage. This price is very competitive for the industry, although it is a very low quantity. The price difference with the $LCoH_{User}$ is related to the small ratio of the hydrogen exports against dispensed hydrogen, and that the exported hydrogen does not use the dispensing equipment. Therefore a lower LCoH can cover the transportation, production and other costs.

As a broad calculation, the average petrol price in The Netherlands for 2018 was around €1.7/liter [119]. Adjusted with inflation to 2030 would result in €2/liter. Assuming a fuel economy of 5 l/100km [44], based on real-world measurements, the cost per km would be €0.1/km in a petrol vehicle, and €0.040/km for FCEVs with the proposed $LCoHUser$. However, fuel prices are known to fluctuate daily due to production and geopolitical reasons, so this comparison is only a reference of possible passenger transportation costs per kilometer.

5.3. COMPARISON TO EXPECTED HYDROGEN ECONOMY IN 2030

Currently, there are multiple proposals for hydrogen production with wind turbines. Depending on the location, scale and business case, proposals vary in capacity, centralized or decentralized, or hydrogen transportation methods.

The proposal from HYGRO, in The Netherlands, is to produce hydrogen directly from the wind turbine, using 4.2 MW wind turbine and a 2 MW electrolyzer on the wind turbine nacelle [120]. The company expects to produce hydrogen at 3 €/kgH_2, delivered at low pressure at the base of the wind turbine tower. Their business case includes a connection to a HFS and a warehouse with fuel cell forklifts.

At a larger scale, the Norwegian company NEL proposed a 20 MW electrolyzer facility, powered by renewable electricity at 40 €/MWh [121]. The company claims an estimate cost to the user of 5 €/kgH_2 with the following LCoH distribution:

- Production: 2.5 €/kgH_2 (51 %)
- Distribution: 1.3 €/kgH_2 (27 %)
- Dispensing: 1.1 €/kgH_2 (22 %)

These values are in line with the results of the proposed HFS configuration (Table 5.2), with similar final hydrogen prices for the final consumer. The main different is regarding transportation, as the proposed HFS produces most of its hydrogen on-site. The end goal of these systems is to achieve a price of hydrogen similar to the cost of gasoline or diesel. Cost parity should be reached at around 2-3 €/kgH_2, depending on the market, local taxes, and user demand.

For The Netherlands, the expectation from van Wijk [1] is to reach hydrogen production price of 2-3 €/kgH_2 in 2030. This also includes limitations on the emissions from hydrogen production, as it is based on offshore wind energy.

5.4. NATIONAL IMPLEMENTATION

The GIS study from Chapter 2 indicated that there are 106 fueling stations in The Netherlands that are eligible to implement the proposed HFS. Taking the performance results from the recommended system, from the selection process in Chapter 4, the requirements and impact of a national implementation were calculated.

The total CAPEX necessary for the total project would be €1.4B. This neglects the possible economies of scale that could lower the total cost per system. Per year, more than 34,700 tH_2 would be produced by the combined systems, enough for FCEVs to travel approximately 4.3 billion kilometers. This number is assumed to grow as the efficiency of FCEVs increases during the lifetime of the HFS. With the extrapolated 15,000 km/year driven per passenger vehicle in 2030, the produced hydrogen would allow to fuel around 289,000 FCEVs. This is approximately 3% of the expected 9.6 million passenger vehicles for that same year.

As indicated in Section 1.1, in 2015 the Dutch transportation sector was responsible for 33 MtCO_2 equivalent gasses. Assuming 106 gCO_2eq/km for the Dutch vehicular fleet [25], ICE vehicles would produce 563 ktCO_2eq to drive the same amount of kilometers as the FCEVs fueled by the HFS. The emissions produced by the HFSs combined amount to 95.3 ktCO_2eq. This results in an emissions reduction of 83%, comparing FCEVs to the emissions of ICE vehicles in the same traveled distance. Assuming an efficiency of 15 kWh/100km for a passenger EV [117], the same driven distance would emit 97.5 ktCO_2eq, meaning a 2.3% difference. However, if the EVs were charge with wind electricity, emissions would only reach 4.5 ktCO_2. For FCEVs and EVs to have similar emissions, the grid emissions should be lower than 200 gCO_2/kWh.

The non-emitted 467.7 ktCO_2eq are just 1.4% from the total annual transportation emissions in The Netherlands. However, this indicates that hydrogen produced with cleaner electricity would provide even more environmental benefits. At a larger scale, with the integration of fuel cell trucks and light-duty vehicles, emissions could be reduced at a faster rate.

5.5. SUMMARY

The recommended HFS configuration detailed in this Chapter shows that it is capable of covering the demand using a high percentage of wind electricity. The grid connection acting as a backup allows to cover almost the remaining hydrogen demand, although it involves very high emissions per kg of hydrogen produced.

The initial investment is high, reaching over €13.2M, but these prices are expected to decrease as the technology is developed further and economies of scale start to play a role. Regarding OPEX, the grid costs are considerable, even with industrial prices for electricity. If hydrogen is always available from outside sources, is more viable to buy hydrogen from an external source and reduce the onsite production to reduce CAPEX and OPEX.

The $LCoH_{User}$ is €5.034/kgH_2, in line with current estimations for future hydrogen prices produced by electrolysis. This is a competitive price, achieving a 60% reduction in cost per kilometer with the expected efficiency of FCEVs in 2030, compared to ICE vehicles.

National implementation requires the additional demand to be present, but it allows to cover most areas of The Netherlands, and a high number of FCEVs, by connecting the main cities in the country. These stations can be the first step to support large scale hydrogen production and FCEVs adoption.

Chapter 6 covers the main conclusions of this investigation. Recommendations for implementation and improvements to the proposed model are also discussed in the following Chapter.

6

Conclusions and Recommendations

6.1. Conclusions

The aim of this report was to identify the feasibility of modifying existing petrol fueling stations to create wind powered hydrogen fueling stations in The Netherlands. Locations were selected, according to wind turbine placement regulations, from the existing fueling stations. The hydrogen fueling station model was proposed, including the control strategy, main components and performance metrics. Multiple capacities of wind power, electrolyzer and grid connection led to 90 system configurations. After evaluating the model with the performance metrics, the configuration with a 4.2 MW wind turbine, 45 kgH_2/hour PEM electrolyzer (2.4 MW) and 1 MW grid capacity was recommended for implementation, based on a case study in Zoetermeer.

The initial selection of the locations for the HFSs was done using GIS. From two different datasets, about 97% of the existing fueling stations were eliminated by multiple filters. The filtering was done based on proximity to existing wind turbines, airports, residential areas, and environmentally protected areas. After removing infeasible location with the proposed filters, a total of 106 existing fueling stations were selected for the implementation of a HFS with a wind turbine for on-site hydrogen production.

The benefit of this tool is that is allows to handle and visualize large data sets, and filter, measure or modify them as needed. However, the accuracy of these data sets is related to the representation of real conditions, thus having updated datasets from reliable sources is highly recommended.

One big challenge was to define the correct setback distances according to Dutch legislation. Most regulations depend on site studies and therefore most of the filtering categories were done based on approximations. This means that the resulting 106 locations could be too strict, removing fueling stations with good conditions for a HFS. The fueling stations eliminated by the ecological network, around 200, are the ones that pose the biggest uncertainty, as the 1,200 m setback distance could be reduced in some cases. This would improve the HFS distribution in the southern provinces.

Hydrogen demand had to be extrapolated to 2030, the year when the HFS was assumed to be implemented. This resulted in 302,560 kgH_2 that have to be dispensed per year by the HFS. The main assumption for the demand was that a HFS will supply enough hydrogen to travel the same accumulated distance as the distance travelled by ICE vehicles fueled by a single average petrol station. Growth in demand up to 2030 was estimated with the growth of vehicular fleet and traveled distance per vehicle.

Seasonal, weekly and daily fluctuations were considered to shape the hourly demand profile in one year.

The demand profile has the limitation that it does not increase over the lifetime of the system and only included passenger vehicles. The introduction of heavy and medium duty trucks, scooters and other FCEVs should be included in the demand for a more accurate interpretation on the fuel demand.

FCEVs depend mostly on fueling infrastructure to support an increase in production. As the actual production of FCEVs is limited, the demand assumption might be too optimistic. The demand profile used for the HFS model is assumed to cover 2,590 FCEVs per year, but additional production and imports mean that 2,836 FCEVs could be supplied with hydrogen. In case of lower demand, the hydrogen from the proposed HFS could be exported to other HFS. Also, the HFS should be equipped with EV charging stations, as the aim of these systems is to reduce emissions from transportation, so supporting other growing EV platforms should be within the possibilities.

The proposed model was designed as simple as possible, considering the main components that require relevant initial investment and operation and maintenance costs. Efficiencies, which often depend on the load of the equipment, were set to static values. The dynamic behaviour of these components, aside from the power curve of the wind turbine, were not included. The sizes were defined according to the demand and known capacities used within the industry, aiming to have a better representation of a realistic HFS system.

Hydrogen storage of 1,000 kgH_2 was appropriate for the demand of the HFS, as not many hydrogen imports were needed throughout the year. A larger capacity tank was not necessary due to the capacity of the electrolyzer and the demand rate. If hydrogen pipelines are implemented in the future by re-utilizing the existing natural gas grid, local storage tanks could be reduced and eliminate the need for tube trailers.

The use of the grid capacity as a backup for the wind electricity has mixed results. It allows to increase the reliability by buying the required electricity, increase revenue, and use of the wind turbine by selling electricity back to the grid, thus avoiding the curtailed power due to storage limitations. However, purchased electricity with high emissions (150 gCO_2/kWh for the Dutch grid), reduces the environmental benefits of hydrogen when produced with electrolysis. Also, it requires important OPEX costs that increase the final hydrogen price to the user. The hydrogen pipeline would eliminate the need of the grid, as in theory there would always be a hydrogen backup source for the HFS.

The recommended HFS configuration achieved more than 95% reliability in terms of meeting hydrogen demand. Capacity factors for the wind turbine and electrolyzer were 39% and 83%, respectively. High equipment utilization was key to reach a low $LCoH_{User}$ at €5.034/kgH_2. The system benefits from a higher capacity wind turbine by reducing emissions, purchasing less electricity from the grid, and selling more electricity to the grid for additional revenue. Average emissions for the hydrogen produced by the HFS are 2.74 $kgCO_2/kgH_2$, a 60% reduction from the estimated 7 $kgCO_2/kgH_2$ produced by SMR. This reduction is also possible by selling wind electricity, which produces 5-8 gCO_2/kWh, removing greenhouse emissions from the electric grid.

Evaluating the performance metrics was fundamental to compare the proposed HFS configurations. Technical performance metrics are straight forward and can be adjusted to every component of the system according to its function. Financial metrics define the final cost to the user, but can vary greatly when considering special interest rates for renewable energy projects, tax exemptions, subsidies or other benefits. No subsidies or similar economic benefits were included in the model. The environmental metrics were used as a reference, as there is no certainty on the emissions of the electric grid and their status in 2030 as the world shifts to more efficient and cleaner technologies. This uncertainty reduces the accuracy of the final results, but helps to identify trends that point at better system designs.

The implementation at a national scale, based on the GIS analysis, is only an indication of the large scale possibilities of the system. It requires an investment of €1.4B to provide hydrogen for 289,000 FCEVs. There will be locations with different demand patters and wind speed profiles. If these systems are coupled together and the local storage is adjusted accordingly, the need for the hydrogen pipeline connection is reduced. Larger grid connections could be implemented in locations close to medium voltage transmission lines, specially if the emissions from the grid are low.

Main findings, based on the literature review, and model simulations:

- Only 106 fueling stations in The Netherlands are feasible locations for wind powered HFSs with on-site hydrogen production (2.7 % of the existing petrol fueling stations).
- An average HFS in The Netherlands will have a demand of 302,560 kgH_2 per year.
- The recommended system to reach the annual demand consists of a 4.2 MW wind turbine, a PEM electrolyzer capable of 45 kgH_2/hour (2.4 MW), and a grid capacity for the electrolyzer of 1 MW.
- Producing hydrogen with wind electricity on-site results in cleaner hydrogen than from SMR, at 2.74 $kgCO_2/kgH_2$.
- An $LCoH_{User}$ of €5.034/kgH_2 results in cheaper transportation costs per km than using ICE vehicles.
- The use of a grid connection improves reliability but is an important driver of OPEX costs.
- National implementations, considering the 106 locations, would provide the annual hydrogen demand for 289,000 FCEVs (3% of the expected passenger vehicle fleet in 2030).

Hydrogen can help the transition to greener transportation. However, the lagging fueling infrastructure is holding the roll-out of more FCEVs. The proposed HFS model and configuration aims to help the start of distributed hydrogen dispensing, which can be later supported by large scale hydrogen production facilities.

6.2. RECOMMENDATIONS

The model developed in this study can be used as a starting point to design a HFS. The investigation presented within this document can be improvement and further developed. Data can be updated and adjusted to a more detailed timeframe than hourly profiles. Different locations can be compared with the same HFS configurations, or even compared to the conditions in other countries. This includes the revision of the setback distances, to avoid removing feasible locations with too strict regulations.

The efficiency profiles can be added to components like the electrolyzer and compressors. Also the dispense and loading/unloading time of the tube trailer can be added to improve the real hydrogen storage fluctuation.

Hydrogen demand can be adjusted to a known profile from an industrial location. Logistic fleets and warehoused with FCEVs have known demand profiles, helping to make the sizing of the system more accurate. As fuel cell trucks, forklifts and other transport equipment starts being deployed, the recommended HFS can be an option to produce green hydrogen on site. This would help to compare costs of running the vehicular fleet, as well as emissions. These locations usually have large covered areas that could include solar panels. Including solar energy would reduce the need or capacity for a grid connection, as solar electricity peaks in the summer.

The HFS could also include electric vehicle charging stations. These charging stations are more common along highways and near urban areas, and can be powered directly from the wind turbine and/or and additional solar photovoltaic installation.

Marine applications could also be studied. Fuel cell boats could refuel at shore, where the wind turbine would have a better energy output due to higher wind speeds.

Hydrogen pipelines should be added to the list scenarios. A hydrogen pipeline connection provides the reliability and makes a grid connection unnecessary. It also provides a reduction in costs and emissions, thus helping the main objective of reducing emissions to the environment.

A

LEGISLATION FOR WIND TURBINE SETBACK DISTANCES

Table A.1: Legislation used to define the setback distances for the GIS filtering process.

Legislation/Regulation	**Purpose**	**Source**
Environmental activity regulation	• An acoustic study is necessary, as stated in Appendix 4 of the Spatial Planning Act (WRO).	• Environmental activity regulation • Spatial Planning Act
Vision for inland wind energy	• Noise from wind turbines: Average wind turbine noise level throughout the year should be ≤ 47 dB$_{Lden}$, according to the Activities under the Environmental Management Act. • Location specific risks: Wind turbine blade failures and fragments. • Turbulence may be present up to 16 rotor diameters downwind from the wind turbine.	• Structural vision for inland wind energy
Wind turbine placement	• Distance suggestions between wind turbines and buildings, roads, and other public infrastructure waterways, underground and above ground pipelines, railways, electric infrastructure, etc. • The distance from residential areas is defined by the maximum throw distance.	• Handbook of risk zones for wind turbine placement
Wind turbines around public infrastructure	• Along national roads, the placement of wind turbines is permitted at a distance of at least 30 m from the edge of the pavement or at a rotor diameter greater than 60 m, at least half the rotor diameter. • Within 30 m from the edge of the pavement and on parking places and petrol stations located along motorways, as referred to in the Rules and Regulations of Traffic and Traffic Signals 1990 article 1c.	• Policy for wind turbines in, on or over public infrastructure
ICAO Annex 14	• Sections 4.3.1 and 4.3.2 mention that high objects should be considered by local authorities to determine effects on the airport operation. • Section 6.2.4 mentions marking and lighting for wind turbines with tip height above 150 m.	• ICAO Annex 14
Ecological and natural protection law	• Definition of standard setback distances and impact from the surface area of wind farms. • There are special cases that are considered by a court, making the safety distance vary considerably. • Most species have a 600 m setback distance as a recommendation, based on similar regulations in Germany, while geese have special protection zones with up to 3km of setback distances.	• Ecological and natural protection law

B

ADDITIONAL REFERENCE DATA

Table B.1: List of GIS data sets used in the filtering process.

Data set	Publication date	Publisher
Airports	2017	Euro Geographics
Land use	2017	Open Street Maps
Netherlands map and statistics	2015/2016/2017	Statistics Netherlands (CBS)
Petrol fueling stations	2017	GPS-Data-Team, Open Street Maps
Protected sites	2012	National Georegister
Regional electric grid	2017	Stedin
Roads and highways	2017	Open Street Maps
Wind turbines	2017	National Georegister

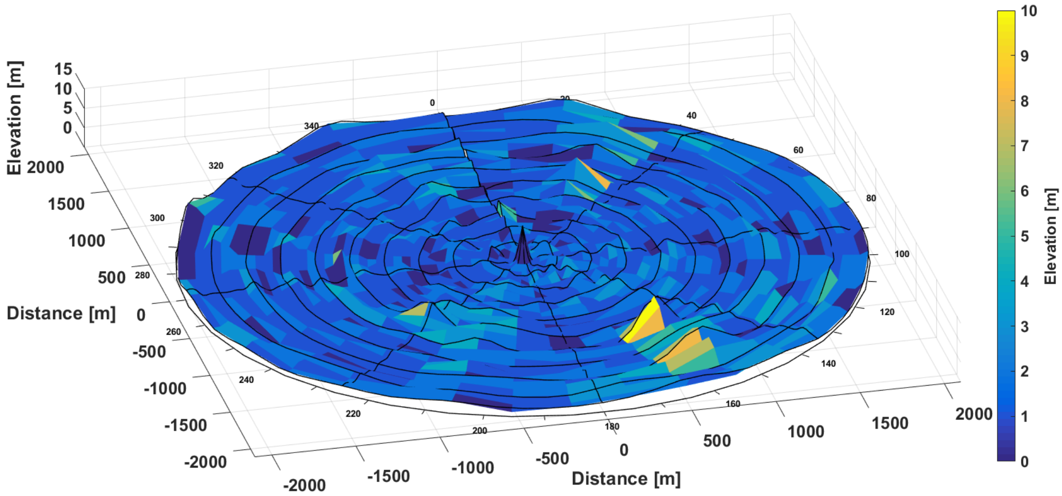


Figure B.1: Terrain roughness profile for the weather station in Voorschoten, in a 2 km radius. The center peak represents the 10m height of the wind speed and direction sensors. North=0°.

Table B.2: Mesoscale surface roughness for different land use categories [42].

Description	z_0 [m]
Open sea	0.0002
Small lake, mud flats	0.006
Marshland	0.03
Pasture	0.07
Dunes, heath	0.1
Agriculture	0.17
Road, canal (Tree-lined)	0.24
Orchads, Bushland	0.35
Forest	0.75
Residential (H <10m)	1.12
City center (High raise buildings)	1.6

Table B.3: Fuel cell vehicles available in the market in 2017.

Specifications	Toyota Mirai 2018[47]	APFCT FC Scooter 2014[53]
Motor Power	113 kW	4 kW
Storage Type (Pressure)	Compressed H_2 tanks (700 bar)	2 x Metal Hydride Canisters (10 bar)
H_2 Capacity	5 kg	2 x 45 g
Refuelling time	5-6 min	30 sec (Canister swap)
Efficiency	100 km/kgH_2	542 km/ kgH_2
Range	500 km	75 km
Price	€80,000	€2,500

C

Complete model results

C.1. Environmental

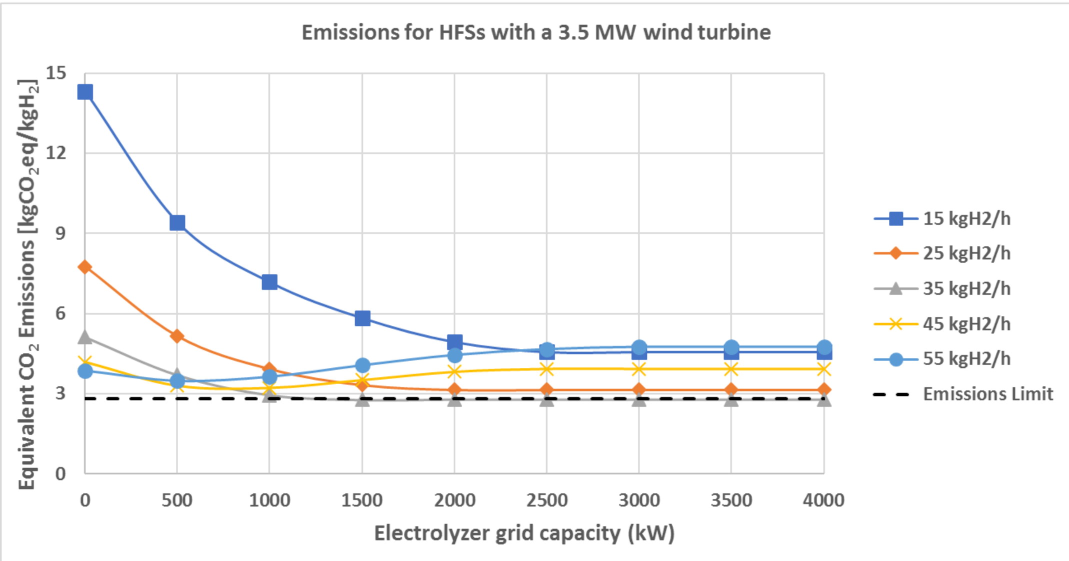


Figure C.1: Emissions results for the HFS configurations with a 3.5 MW wind turbine.

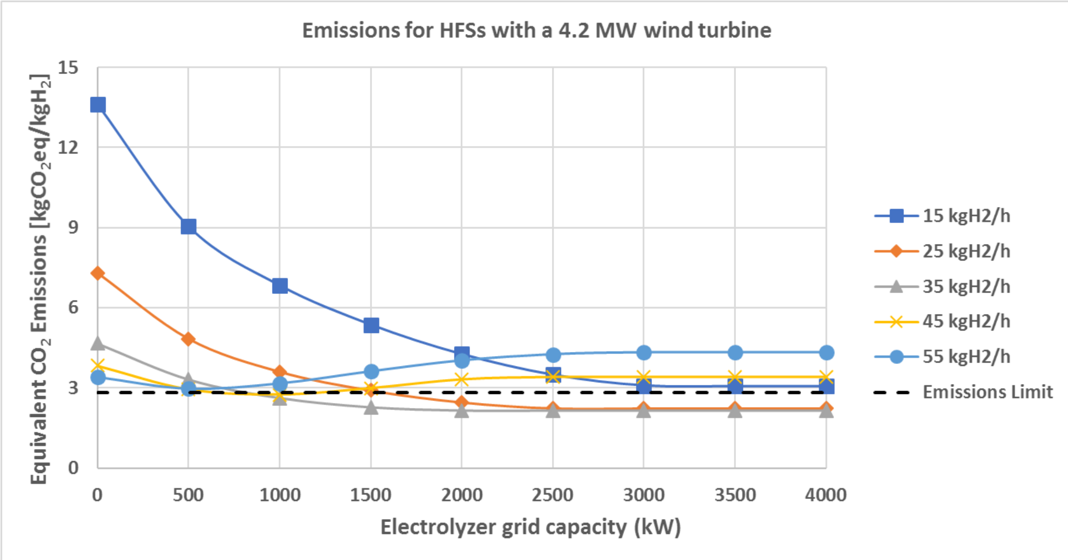


Figure C.2: Emissions results for the HFS configurations with a 4.2 MW wind turbine.

C.2. RELIABILITY

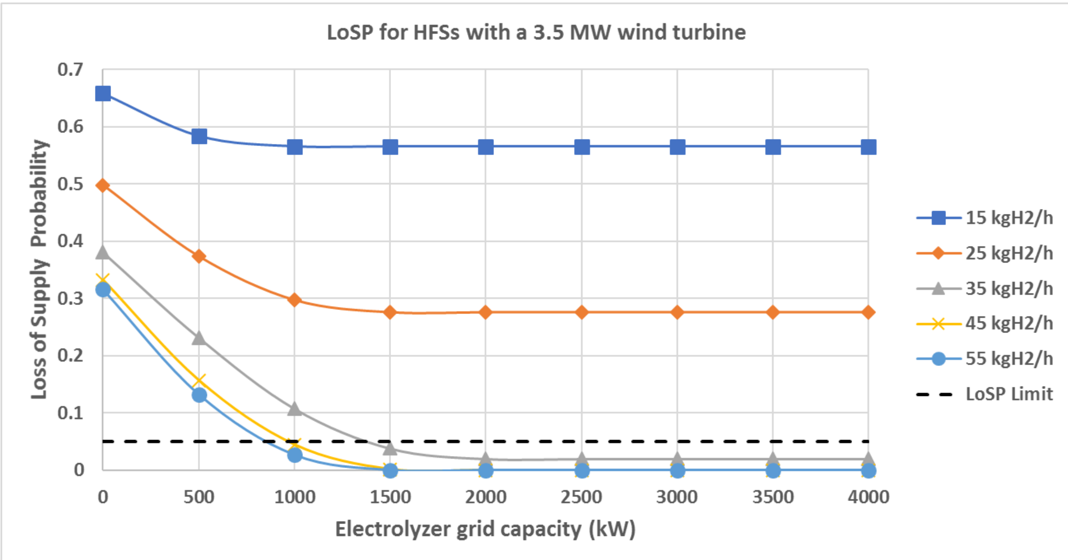


Figure C.3: LoSP results for the HFS configurations with a 3.5 MW wind turbine.

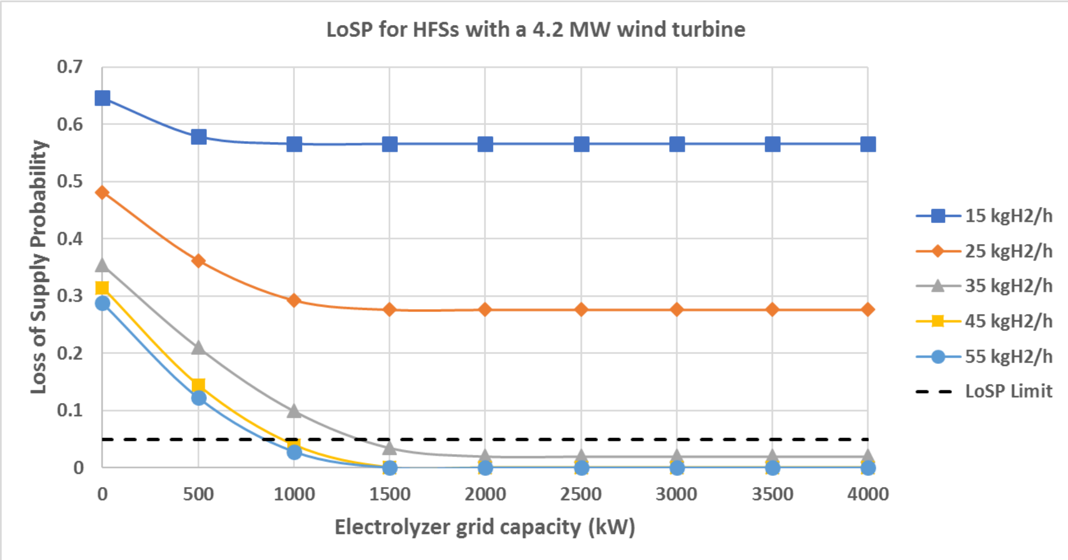


Figure C.4: LoSP results for the HFS configurations with a 4.2 MW wind turbine.

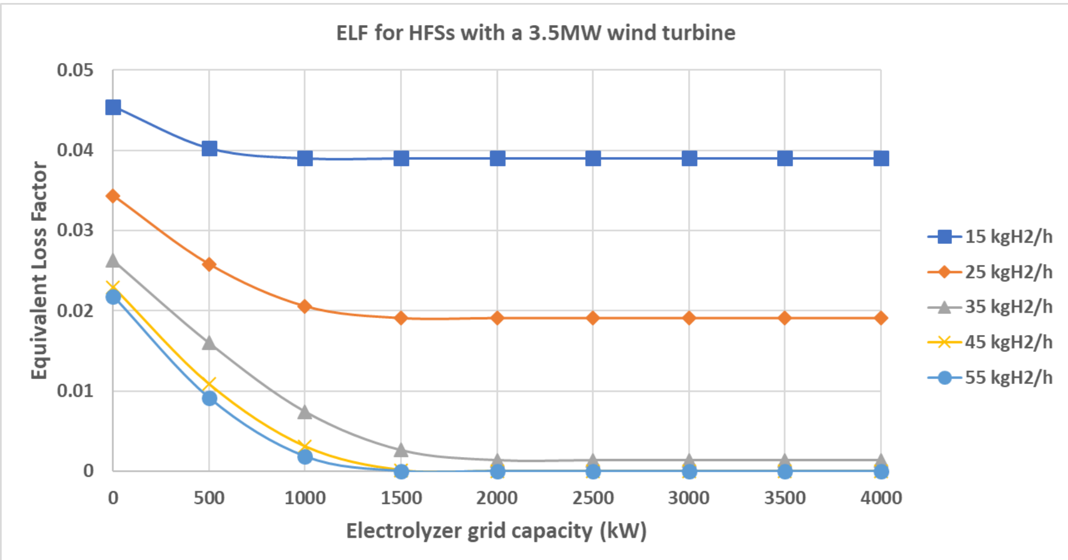


Figure C.5: ELF results for the HFS configurations with a 3.5 MW wind turbine.

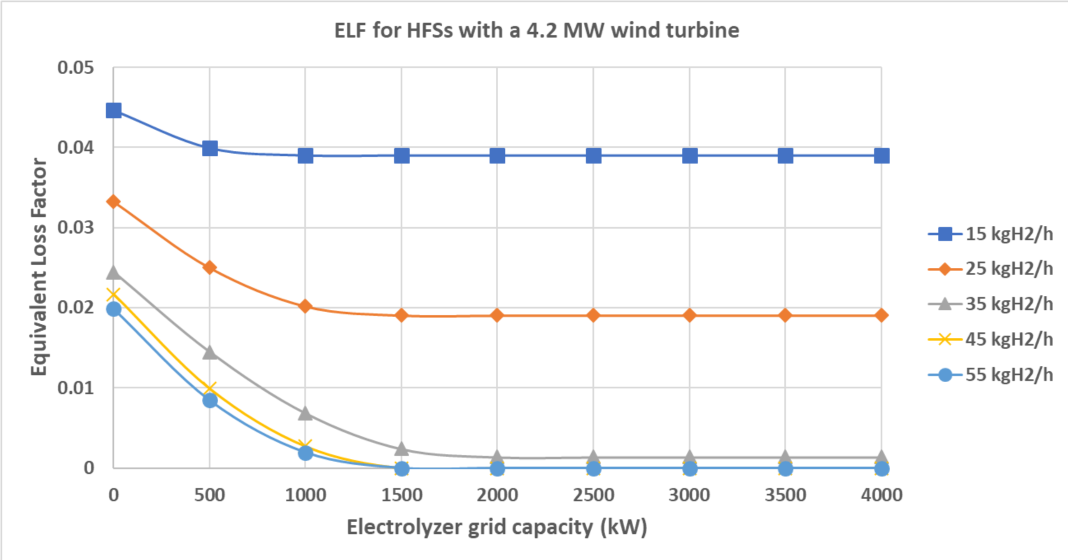


Figure C.6: ELF results for the HFS configurations with a 4.2 MW wind turbine.

C.3. FINANCIAL

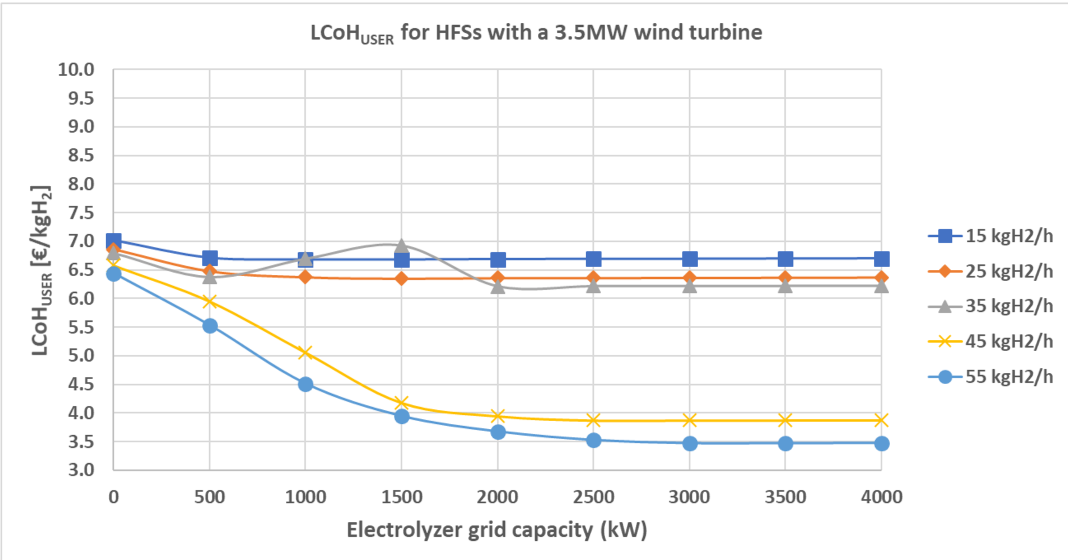


Figure C.7: LCoH$_{User}$ results for the HFS configurations with a 3.5 MW wind turbine.

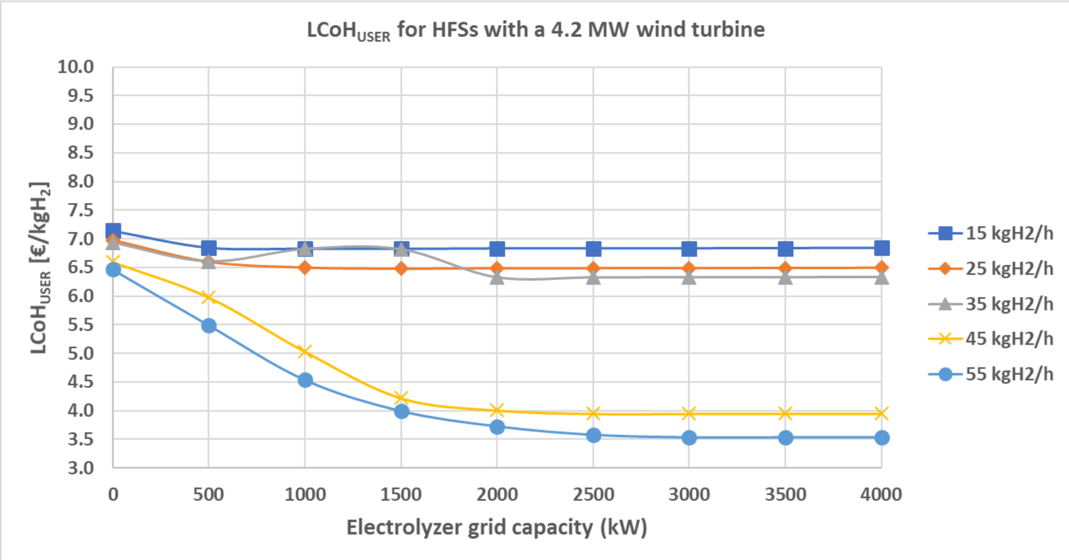


Figure C.8: LCoH$_{User}$ results for the HFS configurations with a 4.2 MW wind turbine.

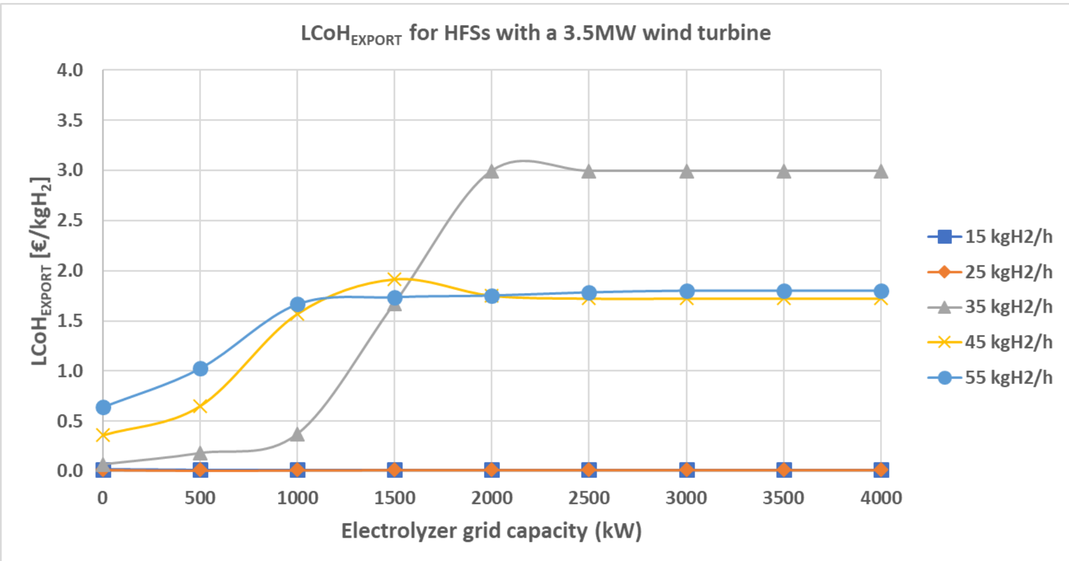


Figure C.9: LCoH$_{Export}$ results for the HFS configurations with a 3.5 MW wind turbine.

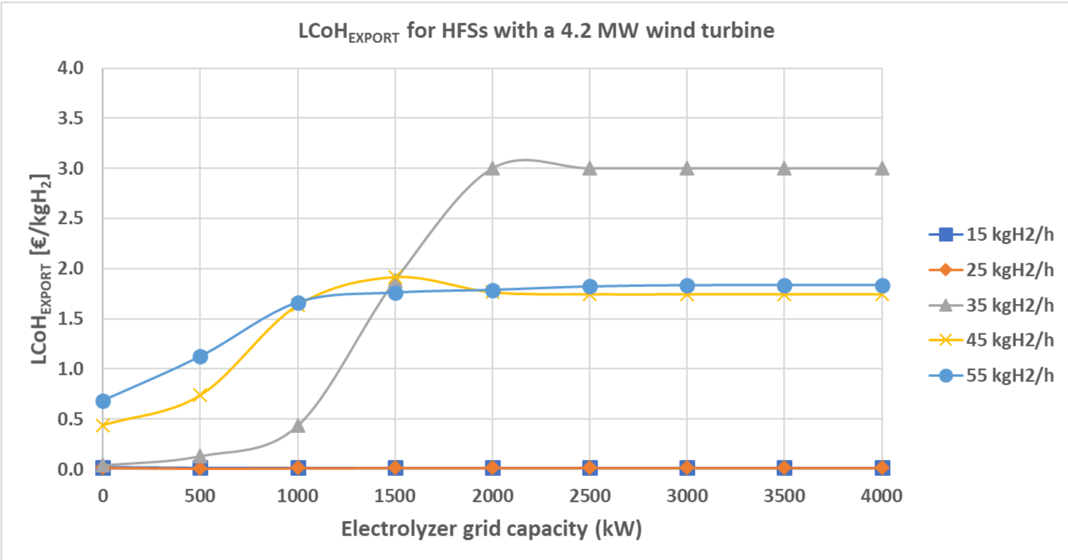


Figure C.10: LCoH$_{Export}$ results for the HFS configurations with a 4.2 MW wind turbine.

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