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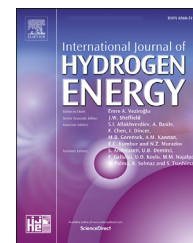# Technical potential of on-site wind powered hydrogen producing refuelling stations in the Netherlands

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HIGHLIGHTS

- 4.6% of Dutch fuelling stations can host wind turbines for hydrogen production.
- Built-up area zoning influences greatly the suitability of the concept.
- These concept stations can produce 2.3% of the demand in a 30% FCEV scenario in NL.
- Per Province stations can produce 0.3%–12% of future mobility hydrogen demand.

GRAPHICAL ABSTRACT
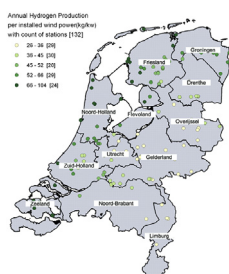
ABSTRACT

This study assesses the technical potential of wind turbines to be installed next to existing fuelling stations in order to produce hydrogen. Hydrogen will be used for Fuel Cell Vehicle refuelling and feed-in existing local gas grids. The suitable fuelling stations are selected through a GIS assessment applying buffer zones and taking into account risks associated with wind turbine installation next to built-up areas, critical infrastructures and ecological networks. It was found that 4.6% of existing fuelling stations are suitable. Further, a hydrogen production potential assessment was made using weather station datasets, land cover data and was expressed as potential future Fuel Cell Electric Vehicle demand coverage. It was found that for a 30% FCEV drivetrain scenario, these stations can produce 2.3% of this demand. Finally, a case study was made for the proximity of those stations in existing gas distribution grids.

Introduction

This study investigates the potential of existing fueling stations in the Netherlands to be converted to on-site wind powered hydrogen producing refuelling stations. We assess the amount of fueling stations, the annual hydrogen production potential, demand coverage and potential to connect to existing gas grids combining several GIS datasets and buffering zones based on current legislation and other criteria. Much of this work was based on the Msc Thesis work [1] and has been extended and detailed within this article. (see Fig. 1)

Hydrogen roadmaps worldwide and in the Netherlands

Numerous countries have released reports giving pathways towards a green hydrogen transition. From Australia [2] to Japan [3] and from California [4] to Europe [5]. All those pathways have a common vision to produce green hydrogen coming from renewable energy resources (wind and solar energy) and utilize in transportation through hydrogen refuelling stations in order to achieve the climate targets. Many of the studies and plans of governments assessed in Ref. [6] indicated that, between 2030 and 2050 Fuel Cell Electric Vehicles (FCEVs) would be cheaper under several circumstances and one of them is the increasing amount of refuelling stations.

In the Netherlands, the cabinet's vision on hydrogen was recently announced, where the roll out of hydrogen refuelling stations is addressed with a vision for 50 stations by 2025 [7]. Also a roadmap with a vision to have a carbon emission free economy by 2050 with green hydrogen as a key ingredient is published [8]. This report vision lies into large cost reductions due to large upscaling of the whole sector coupling with hydrogen, utilizing most of the industrial facilities in the Northern part of the Netherlands. In addition, a report from the gas and electricity transmission operators [9] identifies the electrical grid capacity issues of the Netherlands and the flexibility that the hydrogen gas networks could provide by storing and transporting large amounts of potential energy. Large scale hydrogen production could also seasonally be stored in salt caverns, as Netherlands have large potential of

10.4 PWh [10]. Beside large scale implementation, production more close to the demand and to distribution points of connection could play a significant role for the energy transition.

The study presented here is focussed on the small-scale distributed generation of hydrogen with Power-to-Gas technologies rather than large scale offshore implementation. This is a parallel step needed to bring about innovation, social acceptance and workforce training within the hydrogen transition targets and manage a successful hydrogen station deployment. The studied concept here has similarities with the deployment plans for hydrogen refuelling infrastructure in North-eastern United Stated described in Ref. [11], where on-site stations play a crucial role as hydrogen production factories for off-site stations by saving total investment costs.

Hydrogen refuelling stations in the Netherlands

Globally, there are many initiatives that have studied the optimal sizing and design of a hydrogen fuelling station, safety aspects, distances and risks and many lessons have been learned [12–16]. In Germany, 84 stations are currently operating with a vision of 100 in the course of 2020 [17] from H2 Mobility initiative, while company H-TEC announced a 1 MW electrolyser to be used for decentralised application at wind power plants and hydrogen refuelling stations [18,19]. In California research institutions are already collecting and analysing operational data from nearly 40 hydrogen refuelling stations [20]. The role of hydrogen refuelling stations is also highlighted in Ref. [21] where the Chinese development goal of hydrogen FCEV development is to have over a 1000 stations with 50% renewable sourced hydrogen by 2030 for over a million FCEVs.

This trend starts picking up in the Netherlands as well. Since 2003, hydrogen refuelling stations are under-going operational and closing status [22]. However, with the hydrogen roadmaps mentioned above, more and more initiatives announce their commitment and will to open new hydrogen stations linked to mobility, following global trends. Recent examples are mentioned in Refs. [23–26] where: 20 fuel cell buses and hydrogen refuelling stations are envisioned for Provinces of Groningen and Drenthe by December 2020 and
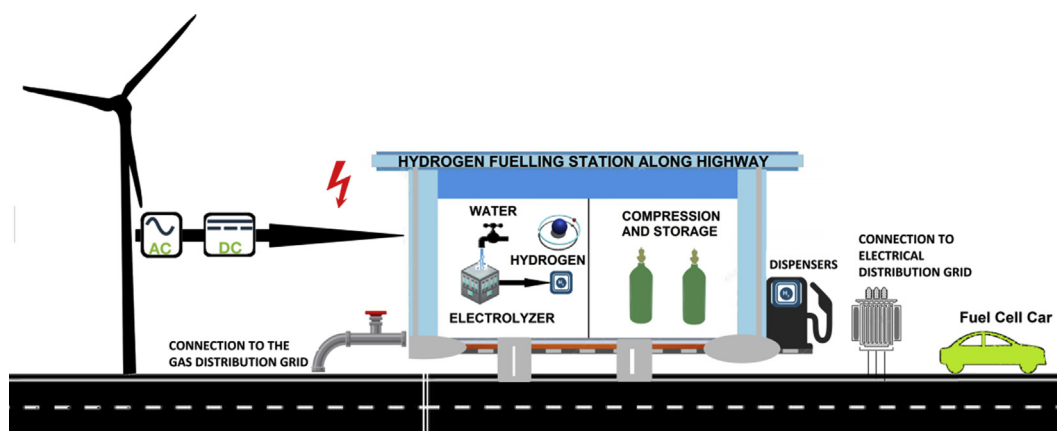

Fig. 1 – On-site wind powered hydrogen production and refuelling station.

openings of hydrogen fuelling stations are announced, while Dutch government set financial incentives for 9 new public hydrogen stations. However, most are still relying on non-renewable hydrogen while having the ambition for green hydrogen. A green hydrogen concept in the Netherlands is from HyGro, where an on-site wind turbine is used for electrolysis for hydrogen production next to a fuelling station [27,28]. A turbine on-site next to an existing fueling station could contribute to cost reductions. This could be realized by coupling the wind turbine directly with an electrolyzer next to where the demand is needed. This would lead in elimination the transportation costs, land reclamation costs, higher grid interconnection costs, behind-the-meter utilization of energy without administrative taxation and eliminating the need to build a new fueling station from scratch.

In this study, we are assuming the concept of on-site wind powered hydrogen producing refuelling stations (or hubs) as in Fig. 1. Initially wind turbines are producing green electricity. The electricity is then directly fed to a Proton Exchange Membrane (PEM) electrolysis hydrogen production unit and a compressor that stores hydrogen in a medium pressure storage or a pressure regulator that feeds in hydrogen to the local high pressure gas distribution grids (4–8 bars). Being connected to the local gas distribution grids provides benefits of blending hydrogen to the local natural gas networks and thus offsetting CO_2 emissions in the short-term, and in the long term providing greater flexibility to the fuelling station assuming that the networks' are converted to 100% hydrogen gas [29]. Blending hydrogen in natural gas networks is technically possible and although it is currently challenging and expensive [30] it is still an option towards the 100% hydrogen economy. Similar system's dynamic operation, excluding connection to gas grids, has been examined in Ref. [31] where it is mentioned that with careful system sizing it is possible to have a self-sustainable fuelling station relying on renewable sources.

The refuelling equipment receives hydrogen either directly after the electrolyser or from the medium pressure storage (typically at 200 bars). In the future scenario of the 100% hydrogen infrastructure, it could also take hydrogen from the gas grid in case of low wind days. This equipment requires electricity to operate. As it was highlighted in Ref. [32], the operation of an H_2 station using combined energy from wind and the electricity grid is preferred as it can increase the amount of cars served. Therefore in our study we assume that the electrical energy for the refuelling processes (dispensing and high pressure compression) is provided by the existing electrical grid nearby the stations. Currently in the Netherlands 80% of fuelling stations are connected to 3×63 A to 3×80 A while the rest 20% are connected to 3×152 A up to 3×250 A, offering fast charging for electric vehicles. Some concepts of fuelling stations have a high peak electrical consumption of ionic compressors (~105 kW) and other equipment [33], while others are on the lower range of 30–50 kW [34]. Thereby we comment that some of the stations might have to slightly upgrade their electrical connection to match those.

GIS and technical potential of hydrogen production

Wind turbines could not be retrofitted in existing fuelling stations which are inside cities and other built-up areas,

ecological parks, airports and other infrastructures due to safety and risk concerns. These set of rules should be taken into account in order to define the technical potential of wind turbines installed in existing fuelling stations. GIS data are being used within GIS software to define all the necessary buffer zones around existing fuelling stations in order to estimate this potential according to the Dutch laws and other criteria.

GIS use in energy system modelling are part of the current energy systems challenges because these are usually considering topological relationships and disregard the geographic relationships. There is a challenge to link the spatial nature of energy systems with not considering only energy-related parameters but also geographic ones [35]. GIS can be used to design the future hydrogen infrastructure and can be an analytical tool at different spatial scales [36]. There are many notable studies that estimate the potential of hydrogen in combination with GIS that have inspired this study in many ways. In our study, we dive deeper by assessing existing locations and areas with constraints derived from legislations and guidelines, rather than optimizing a theoretical scenario which is common in literature.

In [37] the potential of wind-powered hydrogen production for the transportation sector is estimated using local wind resource characteristics, land use constraints with the exclusion of highly elevated areas or highly sloped areas and some constraints regarding infrastructures (such as road networks). The wind turbines are assumed to be installed in all areas available after all constraints with a 10 rotor diameter spacing criteria. In Ref. [38] a GIS-based scenario is made to calculate the investments necessary to envision a pipeline distribution and transmission network in Germany for hydrogen being produced by different scenarios (offshore wind, onshore wind, lignite gasification). Their conclusion is that a smooth transition is needed from the existing situation towards the successful adoption of energy systems. Relying on network of existing fuelling stations and existing infrastructure could facilitate this transformation towards hydrogen economy. This statement is in-line with the current study about retrofitting existing fuelling stations towards on-site wind powered hydrogen producing refuelling stations. GIS are also used in Ref. [39] to analyse hydrogen station roll-out strategy to introduce hydrogen vehicles in Andalusia. Mainly road networks, nodes and population datasets have been used in this study. Finally, an interesting study for Cordoba (Argentina) is presented using GIS for wind resource mapping, hydrogen production estimation, delivery time estimation through road networks and delivery in Cordoba city. This study is quite interesting because it combines as well economic aspects [40].

GIS are also a useful tool for other numerous potential hydrogen applications, such as in Ref. [41] for application of power-2-gas where investment screening was performed by synthesizing GIS data for different power plants for hydrogen production taking into account infrastructures. Also the hydrogen demand for transportation sector is assessed for Algeria in Refs. [42] together with analysis of production costs and environmental benefits. GIS are also used for the study in Germany [43], where a geospatial hydrogen demand-weight distribution is presented for several hydrogen mobility markets (bus, car, train etc.). The study in Ref. [44], makes a

comparison of different alternative vehicle fuelling infrastructure scenario, where GIS is used to assess the time-related proximity and coverage of those stations to the user. Large GIS datasets in combination with wind turbines are used in Ref. [45] for decarbonizing heat with use of hydrogen and inter-seasonal storage. In Ref. [46] energy systems are linked with GIS models for hydrogen infrastructure development. GIS can easily link so many energy system models with geo-spatial data in order to effectively design and quantify costs, infrastructural upgrades and other useful information for policymakers towards energy transition. A holistic approach is presented in Ref. [47] for all potential pathways for hydrogen refuelling infrastructure in Norway where several production technologies beside wind are considered in combination with supply/delivery scenarios.

Reading this literature, we see that GIS have a great potential to help designers, urban planners, energy planners and other stakeholders to effectively design the future energy systems with hydrogen being a key ingredient. Finding and synthesizing the appropriate datasets is key for a successful and understandable assessment.

Outline

In our study we develop a method to assess the technical potential of existing fuelling station to host a wind turbine within their vicinity and classify them based on wind availability, hydrogen production capability and proximity to gas distribution networks, with the vision for covering the fuel cell electric vehicle drivetrain for the future as well as providing flexibility with connection to the gas network.

As a first step, we identify the barriers for wind turbine installation and estimate the amount fuelling stations suitable for conversion to wind powered hydrogen producing refuelling station presented in Chapter 2. Then we estimate the wind production potential based on wind energy resource assessment and relate this to the future hydrogen demand for the transportation sector. We perform a well case study to identify the interconnection possibility with existing gas grids. We discuss the results and derive the conclusions at the end of this article.

Amount of suitable fuelling stations

Methodology

Here we find the amount and the location of the existing fuelling stations that could host a wind turbine within their vicinity for the future on-site hydrogen production. We use laws/guidelines for getting a permit for installation, as a basis to define which of the fuelling stations could to have a wind turbine next to them. We have not considered laws special to hydrogen related installations in this study but we suggest for further investigation.

The fuelling stations have been found through Open Street Maps (see in Fig. 2) which might generate some uncertainty as the persons who are registering these data are individuals. We use buffer zones to define the maximum distances stated by the guidelines.
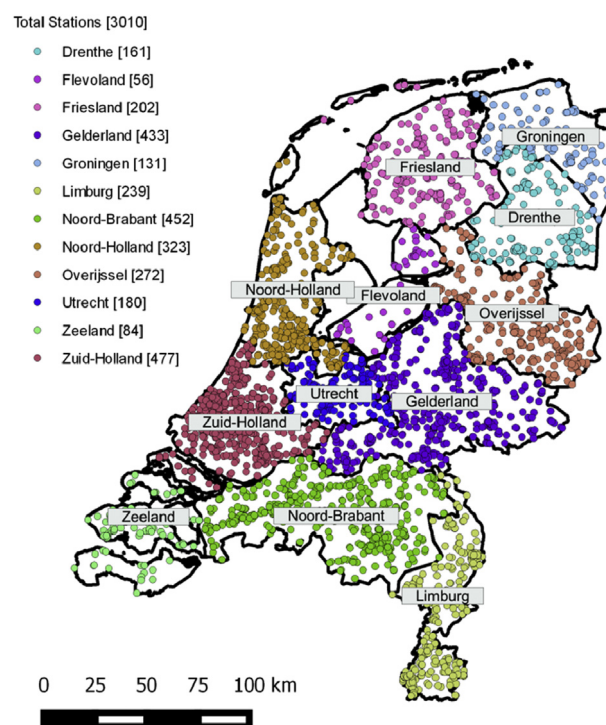

Fig. 2 – Map of all existing fuelling stations from Open Street Map dataset classified by Province.

All the datasets were found online and converted (if needed) into a CRS (Coordinate Reference System) of (EPSG: 28,992, Amersfoort/RD New) for further geoprocessing filtering. The filtering methodology was done with the Difference tool provided by QGIS software.

Below you can see the buffer zone descriptions. The physical notion behind most of those is the maximum throwing distance of an object from a wind turbine during normal operating conditions (for example ice or a detached blade) as has its background in the handbook for risk assessment for wind turbines [48]. There are also other buffer zones with respect to noise and turbulence which are based on environmental and aviation guidelines. The buffer zone description, distance and datasets used are summarized below in Table 1.

Proximity to existing wind turbines
At first we remove the fuelling station dataset where there are wind turbine(s) within proximity of 200 m. These stations could also be envisioned as potential candidates for wind turbine installation for hydrogen production, but for now they are considered part of a different project connected to the electrical grid. The wind turbine data are found in the National GeoRegister of the Netherlands [60].

Built-up areas zoning
This zoning covers vulnerable buildings such as houses, hospitals, schools, restaurants, hotel, office buildings, sport facilities as described in the handbook of risk zoning for wind turbines [48]. The datasets used for this zoning are from Open Street Maps, EuroGeographics and Land Cover and Land Use

Table 1 – Datasets used.

Buffer Zone Description	Buffer Distance	Dataset used
Proximity to existing wind turbines	200 m	[49]
Built-Up Areas	245 m (based on the maximum throwing distance of a 3–5 MW wind turbine at normal operating conditions [48])	[50–52]
Silent Zone Areas	1250 m (based on maximum allowable noise level and a reference turbine)	[53,54]
Airports	2000 m (based on turbulence coming from turbines)	[50]
Railtracks/Waterways/Motorways/Main Roads	80 m (based on ½ rotor diameter of a 160 m wind turbine [48])	[49,50]
Ecological Networks	600 m (based on a median value of most species present in Ref. [55])	[56]
Winter Geese Resting Areas	3000 m (based on criteria in [57]	[58]
High Voltage Lines and High pressure pipelines	245 m (based on maximum throwing distance of a 5 MW wind turbine at normal operating conditions [48]	[59]

Table 2 – Effect of zoning regulations on the amount of fuelling stations suitable for wind turbine installation, for all fuelling station datasets.

Filtering Steps	Station-difference in numbers and percentage from all	
All existing fuelling stations	3021	
Stations no closer than 200 m to existing wind turbines	3011	
Built-Up Area Zoning (allowed stations)	465 (15.3% of total)	
Residential/Commercial/Retail	668	22.1%
Land Cover (discontinuous urban fabric)	851	28.2%
Land Cover (sport facilities)	2810	93.0%
Silent Zones	2781	92.1%
Infrastructure Zoning (allowed stations)	2122 (70% of total)	
Rail Tracks	2923	96.8%
Small Waterways	2959	97.9%
Large Waterways	3010	99.6%
High-Voltage Lines	2871	95.0%
High Voltage Stations	2948	97.6%
Airports	2940	97.3%
High Pressure Pipelines	2448	81%
Environmental Zoning (allowed stations)	1796 (59% of total)	
Natural Ecological Networks	1894	62.7%
Geese Winter Resting Areas	2864	94.8%
Total Results	132 (4.35% of total)	

Finally, another zoning restriction applies for the built environment and is the Silent Zone. It has its origin in the Noise Nuisance Act (Bulletin of Acts and Decrees, 1979). Silent areas were defined therein as areas in which the noise pollution caused by human activities is so low that the natural sounds prevailing in that area are not or hardly disturbed. In the governmental and legal pages in Refs. [54,61], the zones and their maximum allowable limit of 40 dB is mentioned. For an example turbine of 5 MW the limit of 40 dB is found at a buffering distance of 1250 m for wind speeds of 10 m/s as shown in Ref. [62,63]. It is advised that a more thorough, detailed and site-specific noise assessment is needed for each fuelling station but for the purpose of this study we assumed this distance as representative enough. The locations depicted from Refs. [53] with the 1250 m buffer are shown in Fig. 4 below.

Infrastructure zoning
Infrastructure zoning covers railways, waterways, motorways, high voltage electrical lines and stations, airports and high pressure gas networks. Around waterways, rail tracks and motorways the placement of wind turbines is permitted at a distance of at least 30 m from the edge of the pavement or when a rotor diameter exceeds 60 m, at least half the rotor diameter [48]. In this study, we are considering a rotor diameter of 160 m, looking in the future where larger rotors are will be used. Therefore the buffer distance is 80 m. A note is made for the motorways as they are not included because the motorways have a buffer of 80 m while the station has a buffer of 150 m around it, leaving potential space in the back of the station away from the road. However, we consider further investigation for complex road junctions. For overhead high voltage power lines and stations and high pressure pipelines, we use buffer distance of 245 m based on the maximum throwing distance at normal operating conditions [48]. The same handbook of risk zoning advices for high-pressure gas pipelines above ground, to be in a maximum throwing distance at over speeding and asks for an expert assessment on this. Since we do not have enough datasets for the placement of the pipelines and as most pipelines are installed underground [64] we assume the buffer distance of 245 m for those as well. It looks contradictory that the buffers are used for the gas grids while hydrogen production and compression occurs on-site, however we assume that the station is designed holistically taking all necessary risk mitigation strategies from

surveys from the Copernicus institutes. All these datasets were used to validate each other but also include areas that are not present in all datasets as with sport facilities which were not included in Open Street Maps. The buffer distance from all those buildings and areas is defined as the maximum throwing distance in normal operating conditions for a 3–5 MW wind turbine [48] and is 245 m. In Fig. 3, the suitable stations can be located when excluding the built up areas.
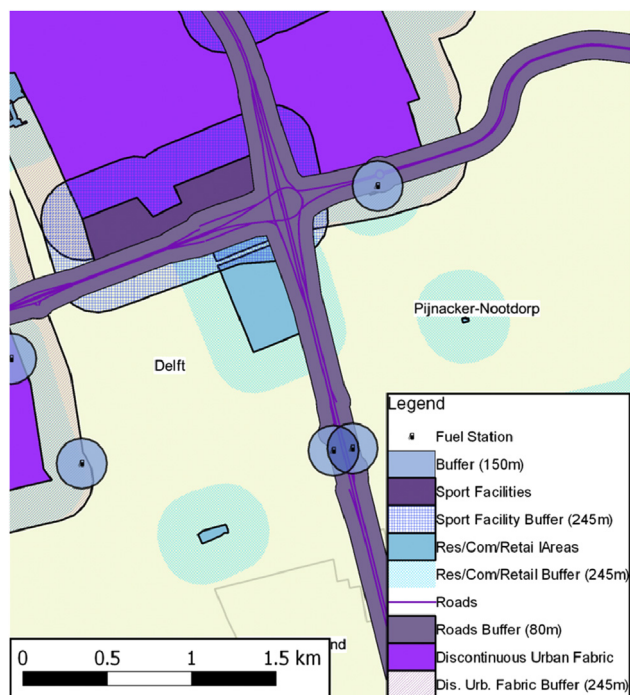
Fig. 3 – Map near the city of Delft with Residential/ Commercial/Retail areas, Sport Facilities, Industrial Areas and Roads with buffer zones.
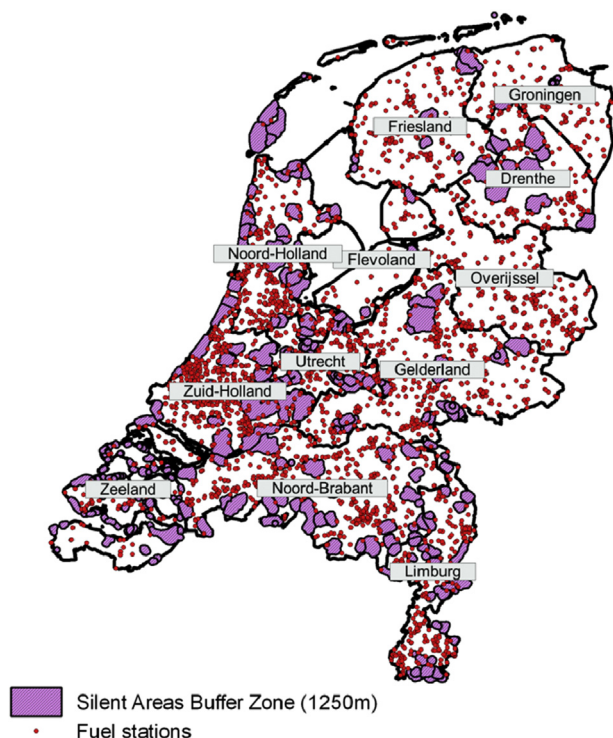
combining wind powered electrolysis with close proximity. More research is definitely needed for this concept.

Finally for airports [65], mentions that high objects should be considered by local authorities to determine effects on the airport operation and refers to the dimensions and slopes of obstacle limitations surfaces. But since this is very site specific, we suggest that more specific studies should be conducted for stations near airports. However, we consider the following study as a baseline for the buffer distance of each airport in the Netherlands, with respect to turbulence effects being noticeable at 16 rotors distances [66], therefore a 2 km setback distance shall be used as "rule-of-thumb" and further investigation is advised. Finally, Fig. 5 shows the location of Schiphol (Amsterdam's airport) and all the infrastructures around it. It is clear that the onshore infrastructure limitations in wind turbine placement are as well numerous like built-up zoning

Environmental Zoning

This zoning covers important natural zones that need to be protected. Especially zones that are natural habitats for breeding or for migration paths. In practise, an environmental assessment is required for each specific installation site with respect to the natural habitat that surrounds the area and the particular species that reside there. This is needed since there are so many different species present which require different buffer distance from the wind turbine nuisance. This has been thoroughly examined in Ref. [55] where a review of several

Fig. 4 – Map overview of existing petrol stations and Silent zone buffers of 1250 m;.
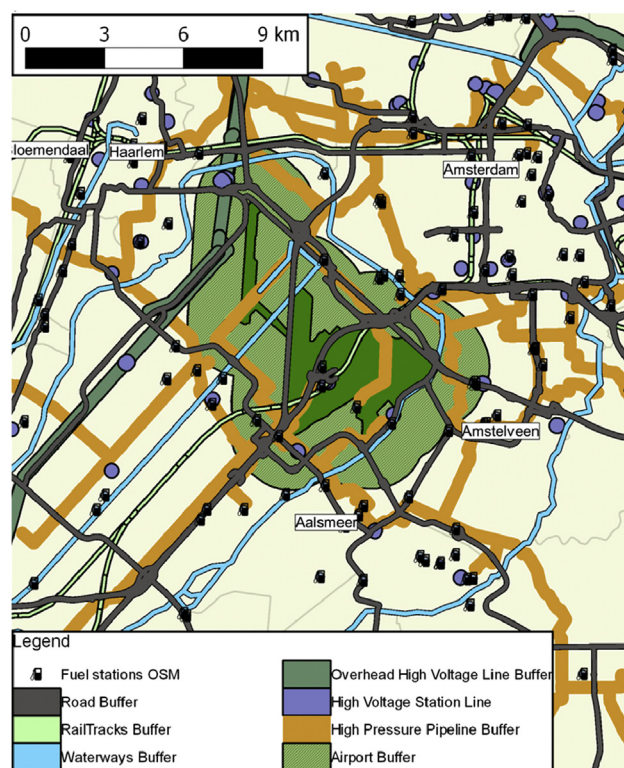

Fig. 5 – Map near Schiphol showing existing fuel stations with Infrastructure Zoning Areas (Airport, High Voltage Lines, Rail Tracks, Waterways, High Pressure Grid).

Fig. 6 — Map overview of existing fuelling stations and the ecological network buffers of 600 m.

environmental articles has been made to define the setback distances for minimum natural habitat disturbance. Most of the results were in between 0 and 600 m but as the authors indicate there can be great variations and for some cases there could be even greater distances (4.5 km) depending on the flight path of certain species. For simplicity, we use the highest buffer distance of 600 m for most species from all the ecological networks datasets used in this study (see in Fig. 6). In that way we can give an approximation of what can happen in a national level. But as explained, it is greatly advised that further investigation is needed and the results are just a rough qualitative estimation of the reduction of the fuelling station suitability. Finally, we remove fuelling stations in proximity of 3000 m (3 km) from Winter Geese resting zones. This is a special zoning advised in Ref. [57] and we include this as an example for bird protection buffer zoning.

Results

After applying all the zoning guidelines with the GIS software we are left with the suitable existing fuelling station that have the technical potential to become the future wind powered hydrogen production and refuelling station that will be part of the transition towards a hydrogen economy. In Table 1 below, we observe that the Built-up are zoning regulations are the highest reduction factor, especially the residential/commercial/retail and Land Cover (discontinuous urban fabric) zoning, allows only 22%—28% from all stations. Environmental zoning allows in total only 59% while Infrastructure zoning allow 70% of the total. The intersection of all remaining stations is 4.35% (132) of the total 3021. This seems little but in

fact these potential pilot projects could be one of the first adopters of this technology in order to act as hydrogen production hubs in order to test and start retrofitting all the equipment needed. Finally, the number of 4.35% could change if more site-specific studies are being performed. These studies might allow more than a single wind turbine to be installed. Most of the zonings applied are based on the handbook of risk zoning for wind turbines which provides guidance/advices and allowable distances for the legal procedure towards getting a permit for installation. To conclude, this study provides a number for planners to take into account towards further energy transition pathways towards hydrogen economy.

Additionally, we classify those with respect to Province level. The following table presents the total number of feasible stations per Province of the Netherlands. We can see that the percentage of feasible fuelling stations with respect to the existing ones per Province ranges between 1 and 12%.

Wind-powered hydrogen production potential at suitable fueling stations

Methodology

Now that all the fuelling stations have been found that could potentially host a turbine, another important step is to identify which of those are worth in terms of available wind energy and their respective hydrogen production. Total Annual Hydrogen Production (AHP) potential is estimated from wind time series and the hydrogen production conversion efficiency. Meteorologists found that it takes at least 5 years for a site to have a typical average wind speed [67]. Therefore, we use the wind time series for each fuelling station from 5-year datasets from the closest weather station from KNMI [68]. The closest station is found through a Nearest Neighbour Analysis among the 47 weather stations of KNMI. The hourly time series of the weather station are translated to the hub height of the wind turbine to be installed at the fuelling station. This is done in 2 steps.

At First, for each time step i wind speed u_i (m/s) is translated to u_{blend} (m/s) at the blending height of 60 m with a log-wind law [69], for which we sample with weighted averages of the surrounding local surface roughness lengths of the weather station for each as seen in the equation below. The roughness lengths z_o(m) are estimated for $10°$ segments for each weather station from the CORINE Land Cover classes [70]. Fig. 7 shows the translated Land Cover map to an equivalent roughness length map with the weather station and the sampling points around it. A set of 4 fuel stations can also be found above the scale bar. These stations use the datasets from the station shown.

$$u_{blend} = u_{ref} \times \frac{\ln\left(\frac{h_{blend}-d}{z_0}\right)}{\ln\left(\frac{h_1-d}{z_0}\right)}$$

In the second step, the time series are translated to the wind turbine's hub height h(m) with the wind power law with the Hellman power exponent a = 0.143, which is applicable for
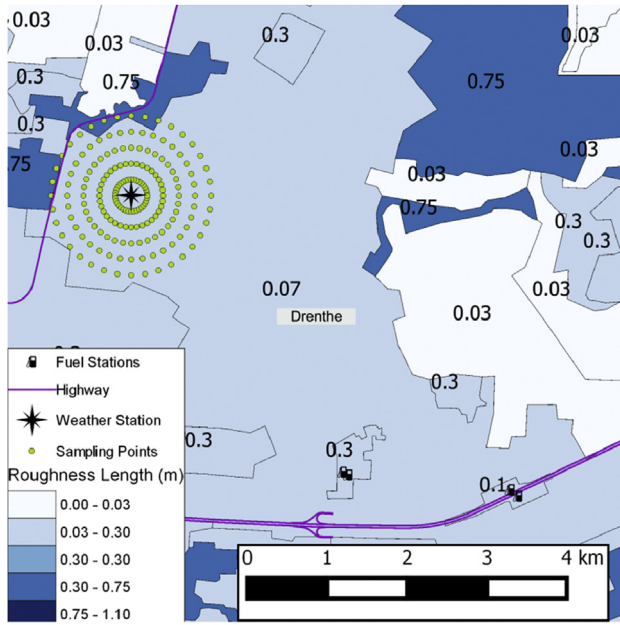
Fig. 7 – Roughness length map used for assessing the wind energy potential of the fuelling stations (1 COLUMN).

open land surfaces, such as the common landscape in the Netherlands [69].

$$u_{hub} = u_{blend} \times \left(\frac{h}{h_{blend}}\right)^{\alpha}$$

Once these are found we are using the Weibull fitting function to find the scale (λ), and shape (κ) parameter of the statistical curve. These parameters provide the frequency where a specific wind speed is occurring through a complete year.

$$f(u) = \frac{\kappa}{\lambda}\left(\frac{u}{\lambda}\right)^{\kappa-1} e^{-(u/\lambda)^{\kappa}}$$

Following, we are using a non-dimensional power curve of Vestas V136–3.45 MW assumed to be installed at a hub height of 112 m [71] in order to express the hydrogen produced per kW installed of wind energy with Power P(u). We have made this assumption for all Netherlands. In reality, for each location and wind characteristics an optimal wind turbine type and hub height would be needed for maximum energy production but is out of the scope of this article.

The Annual Electricity Production (AEP) is estimated with the Weibull probability for each wind speed and the non-dimensional wind power produced at each wind speed for a full year of 8760 h.

$$AEP\left(\frac{kWh}{kW_{installed}}\right) = 8760 \sum_{u=0}^{u=30} f(u)P(u)$$

For the hydrogen production we are assuming a hydrogen conversion efficiency of 53.4 kWh per kg of hydrogen produced from the Near Future scenario 2030 [72]. In reality, hydrogen production efficiency is dynamic and depends on many factors but this number we give a rough approximation of the capability of the station. The following equation is used for estimating the Annual Hydrogen Production (AHP) expressed in kg of hydrogen produced per kW of wind turbine installed.

$$AHP\left(\frac{kgH_2}{kW_{installed}}\right) = AEP\left(\frac{kWh_e}{kW_{installed}}\right) \times \eta\left(\frac{kgH_2}{kWh_e}\right)$$

Further we classify the total annual hydrogen production potential per Province, by simply adding all potential production of each station in each Province. However, it is interesting to observe it in relation with the passenger car fuel demand that it could potentially cover for the future. We estimate this based on the average figure of 13.200 km per year for all cars in the Netherlands [73] and a fuel economy of 1 kg H_2/100 km driven, as it has been published in several car brands that have commercialized fuel cell cars and has been reported in Refs. [21,74]. Finally for the number of vehicles we are assuming that in the Near Future there will be 30% FCEV for the drivetrain of Dutch car, which is an optimistic scenario. We also assume that the number of cars per Province does not change and we use the car registrations and population statistics from CBS (Centrale Bureau voor de Statistiek) datasets from 2018 [75] in order to classify the results per Province.

Even though this approach is over-simplified, assuming an equal amount of hydrogen cars serviced by each station, it still can provide an indication of the possibilities of wind energy to cover a part of the hydrogen demand for mobility. The numbers used in this study are subject to change with future developments in the field. The method described provides us with national level key figures and numbers per Province which are useful for planners. Finally, we strongly suggest for each individual station that a specific system design and sizing is performed taking into account refuelling behaviours and future predictions such as the study in Ref. [76].

Results

7In Fig. 8 we present the graduated green points of Annual Hydrogen Production (AHP) potential per station expressed in kilograms of hydrogen normalized per kW of wind turbine installed. The normalized representation is done so that someone could simply multiply the peak power of a turbine to get a rough estimation of the hydrogen produced for different turbine peak power. Regarding the results, as a logical consequence of the wind resource available near coastal areas of the Netherlands (West and North) the fuelling station with dark green have greater potential compared to the locations in the South-East of the country. For the locations in the South the lower production potential could be optimized by having wind turbines with higher hub heights which provide more energy. Nearly 100 stations can produce between 26 and 66 kgH$_2$ per kW of wind turbine installed capacity while the maximum of all 132 stations is 104kgH$_2$/kW (see Table 3).

In Fig. 8 results are non-dimensional and as explained in the Methodology we used the example of the a 3.45 MW wind turbine to calculate the potential for all Provinces. This amounts to an annual production range of 90−360 tonnes of hydrogen a year per station depending on the wind resource of each location. In Table 4 below we present results in a Province level. The suitable fuelling stations could generate
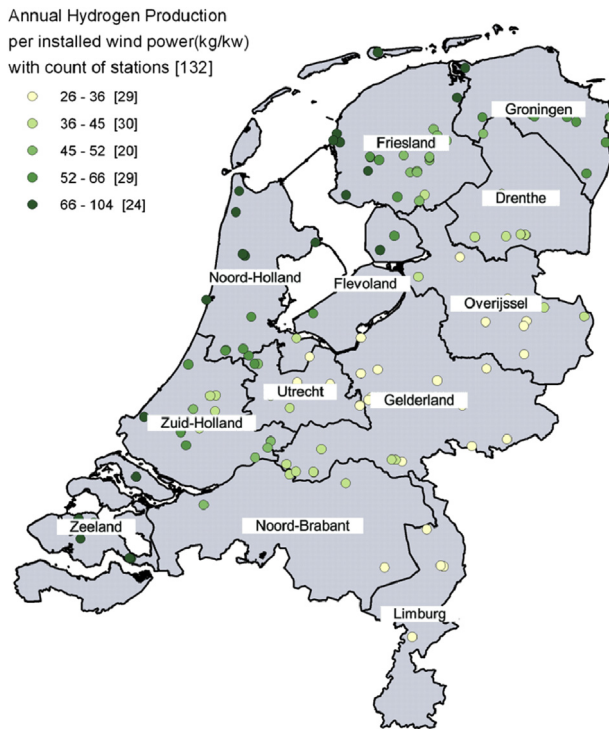
Fig. 8 — Map with the hydrogen production potential per suitable station in kilograms of hydrogen per kW of installed wind turbine capacity with a count of stations for different ranges of results. The greener the station the more production potential.

the annual hydrogen demand of 2.3% of the cars in a 30% FCEV national drivetrain scenario in a configuration with a V112–3.45 MW turbine at each suitable station. This is subject to change depending on the future wind turbine peak power and the possibility to increase the amount of turbines installed next to the fuelling station.

Table 3 — Amount of suitable fuelling stations per Province.		
Province	Existing Fuelling Stations	Feasible Stations (% from total)
Friesland	202	25 (12%)
North-Holland	323	15 (4.6%)
Gelderland	433	19 (4.4%)
Groningen	131	9 (6.9%)
Overijssel	272	9 (3.3%)
Drenthe	161	10 (6.2%)
South-Holland	477	19 (4%)
Utrecht	180	9 (5%)
Flevoland	56	3 (5.3%)
North-Brabant	452	4 (0.8%)
Zeeland	84	6 (7.1%)
Limburg	239	4 (1.7%)

Per Province level, the maximum coverage of the annual demand is observed in the Northern Provinces of Friesland (12%), Groningen (6%), Drenthe (5%) and the coastal Province of Zeeland (6%). For the most populated provinces the range of demand coverage is between 2 and 4% while for the most Southern Provinces is very low from 0.3 to 1%. The Northern areas are less densely populated and that is why there is greater demand coverage.

Case study to assess the possibility for natural gas grid interconnection

In the future, hydrogen gas grids will be a reality and on-site wind powered hydrogen fuelling stations could be an energy hub to deliver "green" hydrogen or receive from the gas grid. This could happen both in the transition phase where hydrogen could be admixed to the grid up to 20% concentrations [77] and in the future with a 100% hydrogen gas grid. Of course up until this future case, many other infrastructural changes would be required with respect to the machinery supporting the hydrogen economy, but this assessment investigates the possibilities with the existing infrastructures thus making the transition faster and more economical.

Fuelling stations are usually close to the distribution gas grid, which is divided into 2 levels in the Netherlands. These are the High Pressure grid (4–8 bars) where small industrial activities are made and the Low Pressure grid (0.03–0.10 bars) which is for residential consumers. Typically, the distribution high pressure grids are connected on one side with the regional gas transmission grid with a gas receiving station, and on the other side with the district stations of low pressure distribution grids going to the residential consumers [78].

For our assessment, we consider the 4–8 bar grids since the amounts of hydrogen produced could be sold directly to residential consumers and small industries beside the hydrogen vehicle demand present on-site. We used Nearest Neighbour Analysis to define the proximity of the centroid that represents the fuelling station towards the closest present pipeline. In this way we could estimate how much pipeline extension would be needed to connect to current gas grids.

The results should not be interpreted as representative for the whole country, as due to limited open data resources from gas distribution system operators (DSOs) in the Netherlands, we only assessed the ENEXIS distribution system operator's (DSO) domain for gas.

In Fig. 9 above, the proximity of the point that represents the fuelling station to the nearest pipeline of 4–8 bars. This method could be used by any gas DSO to estimate how much extra pipeline they would need to manufacture and layout in order to connect to fuelling stations with on-site hydrogen production by wind turbines. For the particular operator, a total of 21.8 km of extra pipeline would be needed for the 23 stations within this operating domain (17.5% of the total of 132 stations). This applies for 5 Provinces (Groningen, Drenthe, Overijssel, Limburg and Noord Brabant) in which 35% of Dutch population lives. For a more detailed view on the distance per station, see below in Fig. 10.

Province	Feasible Stations (%from total)	Total AHP Potential1 (tonnes)	FCEV Car Registrations in a 30% drivetrain scenario2	Coverage of 30% FCEV drivetrain scenario2	Cars Served in 30% FCEV plan
Table 4 – Hydrogen production potential and coverage of all suitable stations for a 30% FCEV drivetrain scenario in the Netherlands.					
Friesland	25 (12%)	5034	303,000	12%	37,846
North-Holland	15 (4.6%)	3443	1,100,000	2%	25,888
Gelderland	19 (4.4%)	2343	955,000	2%	17,613
Groningen	9 (6.9%)	1915	250,000	6%	14,397
Overijsel	9 (3.3%)	1142	530,000	2%	8586
Drenthe	10 (6.2%)	1508	250,000	5%	11,336
South-Holland	19 (4%)	3771	1,475,000	2%	28,352
Utrecht	9 (5%)	1208	585,000	2%	9079
Flevoland	3 (5.3%)	635	175,000	3%	4773
North-Brabant	4 (0.8%)	566	1,235,000	0.3%	4254
Zeeland	6 (7.1%)	1446	195,000	6%	10,869
Limburg	4 (1.7%)	397	555,000	1%	2983
TOTALS	132 (4.35%)	~23,400 tons	~2,280,000 cars	2.3%	~176,000 cars
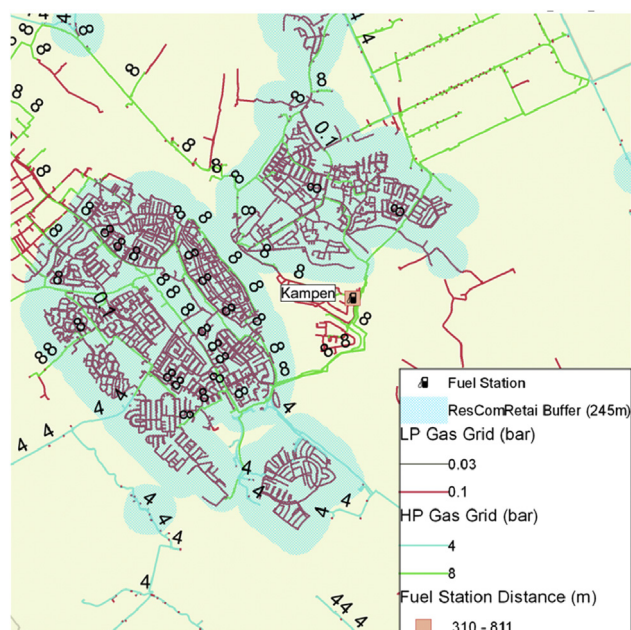
Fig. 9 – Suitable fuelling station for on-site wind powered hydrogen production next to a network of gas pipelines.
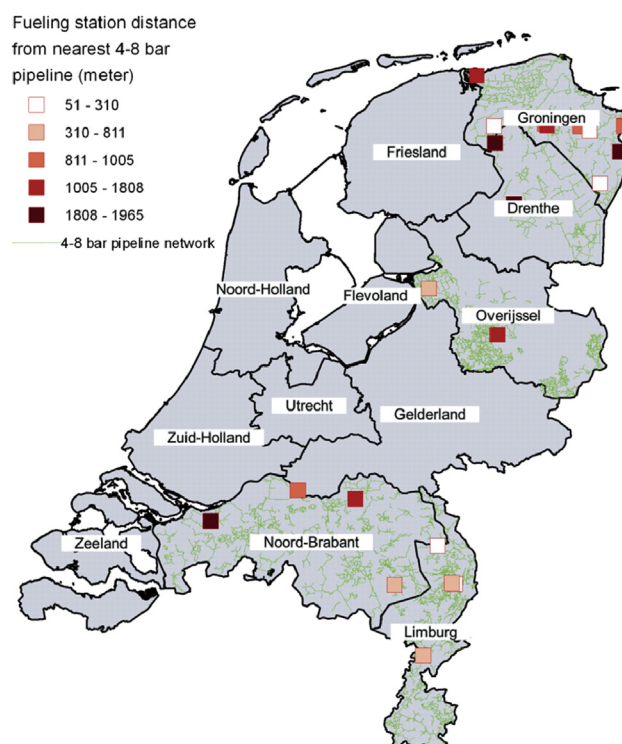
Fig. 10 – Distance of some fuelling stations from high pressure gas distribution grids (4–8 bars) grid.

Discussion

This study shows the technical potential of existing fuelling stations to be converted to wind powered hydrogen producing refuelling station. The utilization of open source datasets was key in order to achieve such a study and it is highly encouraged although uncertainty could be an issue especially for the datasets arriving from Open Street Maps, which are based on individuals to fill in the data. It is an attempt to utilize and synthesize all these data in order to help engineers, scientists

and policy makers to define new steps towards the hydrogen economy seen from this angle of smaller scale projects. This study could be used as a basis for some Dutch system operators in order to assess their future planning activities of interconnecting these hubs with hydrogen pipeline infrastructure. For the ones not assessed, this paper could be used as a guideline and method to estimate how much grid upgrades would be needed for these stations. Additionally, this

study is valuable for future fuelling station retailers and designers who might want to invest in wind powered hydrogen production and could use this methodology as a guideline to assess the feasibility of their station. The results of hydrogen production potential per kW of wind turbine installed capacity presented Fig. 8 could be used as a preliminary rough estimation and first indication of hydrogen production per station per different province and for an assumed wind turbine peak power capacity, as results are normalized. Finally, this study provides useful input in a national level about onshore wind powered hydrogen production next to existing fuelling stations and also quantifies the hydrogen production potential in relation to the future demand of fuel cell electric vehicles. The results are quite promising, given the fact that these stations are only a few stations of all stations of the Netherlands placed mostly outside urban areas.

Finally, we identify some roll-out scenarios based on the infrastructural upgrades and the FCEV uptake for these stations. The infrastructural upgrades refer to whether the natural gas grids will need first to blend hydrogen with natural gas or will directly move to a 100% hydrogen utilization. In the first case, the wind powered refuelling station will be able to inject hydrogen gas in the distribution grid but will need some separation technologies in the case of getting hydrogen from the grid and an intermediate storage for the hydrogen. In the 100% hydrogen scenario, the installation is straightforward with possibilities of injecting when there's production surplus and receiving hydrogen gas when there's hydrogen production deficit by wind turbine and the station's intermediate storage is not sufficient.

Conclusions

This study presented a methodology to evaluate the technical potential of on-site wind powered hydrogen producing refuelling stations. The stations were filtered based on risk zoning guidelines that limit the installation of wind turbines. The main conclusions are:

- The combination of all buffers reduces the amount of suitable fuelling stations to 4.6% of all (132 out of 3021). These can have a wind turbine installation next to them for hydrogen production.
- Built-Up area buffers reduce the amount of the suitable stations to (15% of total), Environmental Zoning to 59% and Infrastructure zoning. to 70%

Then a wind resource model and energy estimation was made to identify the technical potential of wind-powered hydrogen production on each suitable station. The results were also classified per Province and related to an assumed 30% FCEV drivetrain in the future.

- The results were normalized for a 3.45 MW wind turbine power curve and resulted in a range of hydrogen production potential 26—104 $kgH_2/kW_{wind\_installed}$ per year. This range is explained by the different wind resources available at different sites throughout the country of the Netherlands

- A 3.45 MW turbine next to a suitable fuelling station has the potential to deliver 90—360 tonnes of hydrogen a year
- The aggregated results for the Netherlands indicate that these stations can produce 2.3% of the total annual hydrogen demand for FCEV in a 30% FCEV drivetrain scenario.
- The range of demand coverage for different Provinces in the Netherlands for those stations is 0.3%—12% of the future hydrogen demand for FCEV in a 30% FCEV drivetrain scenario
- Northern provinces of the Netherlands have the highest demand coverage from such stations due to their low population density and less zoning restriction for the fuelling stations.

This study provided as well the length of gas grid expansion needed for the stations to be connected for one grid operator in the Netherlands. A total of 21.8 km of pipeline was found needed to connect to those stations in order to export hydrogen in the grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] Rodríguez Escude M, Chrysochoidis-Antsos N, van Wijk A. Power-to-Gas for the Dutch transportation sector: wind-powered hydrogen fueling stations with on-site hydrogen generation. Delft University of Technology; 2019. http://resolver. tudelft.nl/uuid:2a5c0646-dd91-49f6-b604-7cd3843359e5.

[2] Bruce S, et al. National Hydrogen Roadmap - pathways to an economically sustainable hydrogen industry in Australia. 2018.

[3] Basic hydrogen strategy. Ministrial Council on Renewable Energy; 2017 [Hydrogen and Related issues].

[4] Forrest M, et al. The California Fuel Cell Revolution - a vision for advancing economic, social and environmental priorities. California Fuel Cell Partnership (CFCP); 2018.

[5] Fuel Cells and Hydrogen - Joint Undertaking. Hydrogen roadmap Europe - a sustainable pathway for the European energy transition. Fuel Cells and Hydrogen Joint Undertaking; 2019. https://doi.org/10.2843/341510.

[6] Tanc B, Arat HT, Baltacioglu E, Aydin K. Overview of the next quarter century vision of hydrogen fuel cell electric vehicles. Int J Hydrogen Energy 2019;44(20):10120—8. https://doi.org/ 10.1016/j.ijhydene.2018.10.112.

[7] Wiebes E. Cabinet Vision for hydrogen. Ministry of economic affairs and climate; 2020.

[8] van Wijk Ad, Coenen Hans, Reijerkerk Jaco, Alberda Maurits, Buit Luuk, Kasova D. The green hydrogen economy in the northern Netherlands. Northern Innovation Board; 2017.

[9] Infrastructure Outlook 2050 - a joint study by Gasunie and TenneT on integrated energy infrastructure in The Netherlands and Germany. Gasunie and TenneT; 2019.

[10] Caglayan DG, et al. Technical potential of salt caverns for hydrogen storage in Europe. Int J Hydrogen Energy 2020;45(11):6793—805. https://doi.org/10.1016/j.ijhydene.2019.12.161.

[11] Tsuda K, et al. Design proposal for hydrogen refueling infrastructure deployment in the Northeastern United States. Int J Hydrogen Energy 2014;39(14):7449—59. https://doi.org/10.1016/j.ijhydene.2014.03.002.

[12] Siyal SH, Mentis D, Howells M. Economic analysis of standalone wind-powered hydrogen refueling stations for road transport at selected sites in Sweden. Int J Hydrogen Energy 2015;40(32):9855—65. https://doi.org/10.1016/j.ijhydene.2015.05.021.

[13] Deng ZH, Jiang YW. Optimal sizing of wind-hydrogen system considering hydrogen demand and trading modes. Int J Hydrogen Energy 2020;45(20):11527—37. https://doi.org/10.1016/j.ijhydene.2020.02.089.

[14] Pan XM, Li ZY, Zhang CM, Lv H, Liu SJ, Ma JX. Safety study of a wind-solar hybrid renewable hydrogen refuelling station in China. Int J Hydrogen Energy 2016;41(30):13315—21. https://doi.org/10.1016/j.ijhydene.2016.05.180.

[15] Tsunemi K, Kihara T, Kato E, Kawamoto A, Saburi T. Quantitative risk assessment of the interior of a hydrogen refueling station considering safety barrier systems. Int J Hydrogen Energy 2019;44(41):23522—31. https://doi.org/10.1016/j.ijhydene.2019.07.027.

[16] Lipman T, Witt M, Elke M. Lessons learned from the installation and operation of Northern California's first 70-MPa hydrogen fueling station. Int J Hydrogen Energy 2013;38(36):15868—77. https://doi.org/10.1016/j.ijhydene.2013.08.120.

[17] Hydrogen filling station network expansion updates. 2020. Available from: https://h2.live/en. Accessed 2020-34-05.

[18] H-Tec Systems 10 MW PEM electrolyser for hydrogen economy. Fuel Cell Bull 2019;2019:9. https://doi.org/10.1016/S1464-2859(19)30422-5.

[19] German wind park deploys H-TEC PEM electrolyser for fueling. Fuel Cell Bull 2018;2018:11. https://doi.org/10.1016/S1464-2859(18)30422-X.

[20] Saur G, Sprik S, Kurtz J, Onorato S, Gilleon S, Winkler E. Hydrogen station data collection and analysis. 2019.

[21] Hydrogen fuel cell vehicle technology roadmap. In: strategic advisory committee of the technology roadmap for energy saving and new energy vehicles; 2018.

[22] Honselaar M, Pasaoglu G, Martens A. Hydrogen refuelling stations in The Netherlands: an intercomparison of quantitative risk assessments used for permitting. Int J Hydrogen Energy 2018;43(27):12278—94. https://doi.org/10.1016/j.ijhydene.2018.04.111.

[23] Netherlands. 20 Fuel cell buses and hydrogen refuelling stations for provinces of groningen and Drenthe by December 2020. 2019. Available from: https://www.fuelcellbuses.eu/public-transport-hydrogen/netherlands-20-fuel-cell-buses-and-hydrogen-refuelling-station-provinces. [Accessed 25 April 2020]. Accessed.

[24] The Netherlands to expand its H2 infrastructure with OrangeGas' first hydrogen stations. 2019. Available from: http://www.hydrogenfuelnews.com/the-netherlands-to-expand-its-h2-infrastructure-with-orangegas-first-hydrogen-stations/8539111/. [Accessed 25 April 2020]. Accessed.

[25] Dutch government sets its sights on hydrogen - Financial incentives for 9 new public hydrogen stations. 2018. Available from: https://www.pitpointcleanfuels.com/news/dutch-government-sets-sights-on-hydrogen/. [Accessed 25 April 2020]. Accessed.

[26] KWR institute opens green hydrogen filling station for own car fleet. 2019. Available from: https://www.dutchwatersector.com/news/kwr-institute-opens-green-hydrogen-filling-station-for-own-car-fleet. [Accessed 25 April 2020].

[27] Wind-to-Hydrogen (W2H2) - TKI system integration study, HYGRO, ECN, energy valley.

[28] First wind turbine for direct 'green' hydrogen planned in Netherlands. Fuel Cell Bull 2017;2017:10. https://doi.org/10.1016/S1464-2859(17)30392-9.

[29] Mukherjee U, Walker S, Maroufmashat A, Fowler M, Elkamel. A Development of a pricing mechanism for valuing ancillary, transportation and environmental services offered by a power to gas energy system. Energy 2017;128:447—62. https://doi.org/10.1016/j.energy.2017.04.042.

[30] Ogden J, Jaffe AM, Scheitrum D, McDonald Z, Miller M. Natural gas as a bridge to hydrogen transportation fuel: insights from the literature. Energy Pol 2018;115:317—29. https://doi.org/10.1016/j.enpol.2017.12.049.

[31] Zhao L, Brouwer J. Dynamic operation and feasibility study of a self-sustainable hydrogen fueling station using renewable energy sources. Int J Hydrogen Energy 2015;40(10):3822—37. https://doi.org/10.1016/j.ijhydene.2015.01.044.

[32] Nistor S, Dave S, Fan Z, Sooriyabandara M. Technical and economic analysis of hydrogen refuelling. Appl Energy 2016;167:211—20. https://doi.org/10.1016/j.apenergy.2015.10.094.

[33] Bauer A, Mayer T, Semmel M, Morales MAG. Wind B J Energetic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen. Int J Hydrogen Energy 2019;44(13):6795—812. https://doi.org/10.1016/j.ijhydene.2019.01.087.

[34] Brown T, Stephens Romero S, Samuelsen GS. Quantitative analysis of a successful public hydrogen station. Int J Hydrogen Energy 2012;37(17):12731—40. https://doi.org/10.1016/j.ijhydene.2012.06.008.

[35] Resch B, et al. GIS-based planning and modeling for renewable energy: challenges and future research avenues. ISPRS Int J Geo-Inf 2014;3(2):662—92. https://doi.org/10.3390/ijgi3020662.

[36] Agnolucci P, McDowall W. Designing future hydrogen infrastructure: insights from analysis at different spatial scales. Int J Hydrogen Energy 2013;38(13):5181—91. https://doi.org/10.1016/j.ijhydene.2013.02.042.

[37] Siyal SH, Mentis D, Mortberg U, Samo SR, Howells M. A preliminary assessment of wind generated hydrogen production potential to reduce the gasoline fuel used in road transport sector of Sweden. Int J Hydrogen Energy 2015;40(20):6501—11. https://doi.org/10.1016/j.ijhydene.2015.03.108.

[38] Baufume S, et al. GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure. Int J Hydrogen Energy 2013;38(10):3813—29. https://doi.org/10.1016/j.ijhydene.2012.12.147.

[39] Brey JJ, Carazo AF, Brey R. Analysis of a hydrogen station roll-out strategy to introduce hydrogen vehicles in Andalusia. Int J Hydrogen Energy 2014;39(8):4123—30. https://doi.org/10.1016/j.ijhydene.2013.06.087.

[40] Sigal A, Cioccale M, Rodriguez CR, Leiva EPM. Study of the natural resource and economic feasibility of the production and delivery of wind hydrogen in the province of Cordoba, Argentina. Int J Hydrogen Energy 2015;40(13):4413—25. https://doi.org/10.1016/j.ijhydene.2015.01.149.

[41] Nielsen S, Skov IR. Investment screening model for spatial deployment of power-to-gas plants on a national scale - a Danish case. Int J Hydrogen Energy 2019;44(19):9544–57. https://doi.org/10.1016/j.ijhydene.2018.09.129.

[42] Rahmouni S, Settou N, Negrou B, Gouareh A. A GIS-based method for future prospect of hydrogen demand in the Algerian road transport sector. Int J Hydrogen Energy 2016;41(4):2128–43. https://doi.org/10.1016/j.ijhydene.2015.11.156.

[43] Cerniauskas S, Grube T, Praktiknjo A, Stolten D, Robinius M. Future hydrogen markets for transportation and industry: the impact of CO2 taxes. Energies 2019;12(24). https://doi.org/10.3390/en12244707.

[44] Lane B, Shaffer B, Samuelsen S. A comparison of alternative vehicle fueling infrastructure scenarios. Appl Energy 2020;259DOI. https://doi.org/10.1016/j.apenergy.2019.114128.

[45] Samsatli S, Samsatli NJ. The role of renewable hydrogen and inter-seasonal storage in decarbonising heat - comprehensive optimisation of future renewable energy value chains. Appl Energy 2019;233:854–93. https://doi.org/10.1016/j.apenergy.2018.09.159.

[46] Strachan N, Balta-Ozkan N, Joffe D, McGeevor K, Hughes N. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. Int J Hydrogen Energy 2009;34(2):642–57. https://doi.org/10.1016/j.ijhydene.2008.10.083.

[47] Stiller C, Bunger U, Moller-Holst S, Svensson AM, Espegren KA, Nowak M. Pathways to a hydrogen fuel infrastructure in Norway. Int J Hydrogen Energy 2010;35(7):2597–601.

[48] Faasen CJ, Franck PAL, Taris AMHW. Handboek Risicozonering Windturbines. Rijksdienst voor ondernemend nederland; 2014.

[49] Geografische open-data GIS bestanden. 2019. Available from: https://www.imergis.nl/htm/opendata.htm. [Accessed 1 April 2019]. Accessed.

[50] EuroGeographics - open topographic data, Available from: https://eurogeographics.org/products-and-services/open-data/topographic-data/, (Accessed 08/08/2018).

[51] OpenStreetMap data for the Netherlands, Available from: http://download.geofabrik.de/europe/netherlands.html, (Accessed 01/03/2019).

[52] Copernicus - corine land cover 2018 (CLC). 2018. Available from: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018. [Accessed 1 February 2019]. Accessed.

[53] StilteGebieden - protected sites of silent zones, Available from: http://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/cc408b2d-09a6-4b2b-9aa3-b46bfe2f00a5, (Accessed 01/04/2019).

[54] Stiltegebieden - Silent Zoning in the Netherlands, Available from: https://www.atlasleefomgeving.nl/meer-weten/geluid/stiltegebieden, (Accessed 2020-06-02).

[55] Winkelman JE, Kistenkas FH, Epe MJ. Ecologische en natuurbeschermingsrechtelijke aspecten van windturbines op land. 2008. Alterra, Wageningen.

[56] NATURA 2000 areas, Available from: http://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/8829e5dd-c861-4639-a6c8-fdbb6e3440d2?tab=inspire, (Accessed 15/03/2019).

[57] LAG VSW. Recommendations for distances of wind turbines to important areas for birds as well as breeding sites of selected bird species (as at April 2015). Working Group of German State Bird Conservancies 2015.

[58] Geese resting areas, Available from: http://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/search?isChild='false'&resultType=details&fast=index&_content_type=json&from=1&to=20&sortBy=relevance&any_OR__title=ganzen, (Accessed 14/03/2019).

[59] Basisregistraties - kadaster, Available from: https://zakelijk.kadaster.nl/brt, (Accessed 01/04/2019).

[60] Wind turbines in The Netherlands. 2018. Available from: http://nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/home.

[61] Scheme of environmental management activitives - activiteitenregeling milieubeheer. E. Minister of Housing; 2017. S.P.a.t.

[62] Madsen HA. Low frequency noise from wind turbines mechanisms of generation and its modelling. J Low Freq Noise Vib Act Contr 2010;29(4):239–51. https://doi.org/10.1260/0263-0923.29.4.239.

[63] Barlas E, Zhu WJ, Shen WZ, Dag KO, Moriarty P. Consistent modelling of wind turbine noise propagation from source to receiver. J Acoust Soc Am 2017;142(5):3297–310. https://doi.org/10.1121/1.5012747.

[64] Open datasets for gas pipelines in The Netherlands from risicokaart.nl, Available from: https://flamingo.bij12.nl/risicokaart-viewer/app/Risicokaart-openbaar, (Accessed 2020-04-24).

[65] ICAO annex 14 - aerodromes - volume 1 : aerodrome Design and operations. International Civil Aviation Organization; 2018.

[66] CAA policy and guidelines on wind turbines. Civil Aviation Authority; 2016.

[67] Manwell JF, McGowan JG, Rogers AL. Wind energy explained - theory, design and application. 2nd ed. John Wiley & Sons Ltd; 2009.

[68] Uurgegevens van het weer in Nederland - Hourly Data of weather in the Netherlands. 2018-2019. Available from: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens. [Accessed 3 April 2019]. Accessed.

[69] Wieringa J. Roughness-dependent geographical interpolation of surface wind speed averages. Q J R Meteorol Soc 1986;112(473):867–89. https://doi.org/10.1002/qj.49711247316.

[70] Silva J, Ribeiro C, Guedes R. Roughness length classification of corine land cover classes. In: Proceedings of EWEC (European Wind Energy Conference and Exhibition 2007). EWEA; 2007. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.608.2707&rep=rep1&type=pdf.

[71] Power curve of Vestas V136-3.45mw, Available from: https://en.wind-turbine-models.com/turbines/1282-vestas-v136-3.45, (Accessed 03/04/2019).

[72] Oldenbroek Vincent, Verhoef Leendert A, van Wijk Ad JM. Fuel cell electric vehicle as a power plant: fully renewable integrated transport and energy system design and analysis for smart city areas. J Hydrogen Energy 2016;42(12). https://doi.org/10.1016/j.ijhydene.2017.01.155.

[73] CBS Trends in The Netherlands. Central Bureau of Statistics; 2018.

[74] Jennifer Kurtz SS, Ainscough Chris, Saur Genevieve. Shaun Onorato Fuel Cell Electric Vehicle Performance Composite Data Products: Spring 2018. NREL; 2018.

[75] Motorvoertuigenpark; inwoners, type, regio, 1 januari. 2018. Available from: https://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=7374HVV. [Accessed 6 June 2018]. Accessed.

[76] Gruger F, Dylewski L, Robinius M, Stoltren D. Carsharing with fuel cell vehicles: sizing hydrogen refueling stations based on refueling behavior. Appl Energy 2018;228:1540–9. https://doi.org/10.1016/j.apenergy.2018.07.014.

[77] Taminiau F. Hydrogen admixture in the Dutch gas grid. TNO; 2017. https://scripties.uba.uva.nl/download?fid=650367.

[78] Rob van Gerwen RB, Grond Lucas, Hers Sebastiaan, Scherpers Benno. Harry croezen system integration - hybrid energy infrastructure. 2015 [DNV GL/ CE Delft/ Dutch Ministry of Economic Affairs/ Netherlands Enterprise Agency (RVO)].