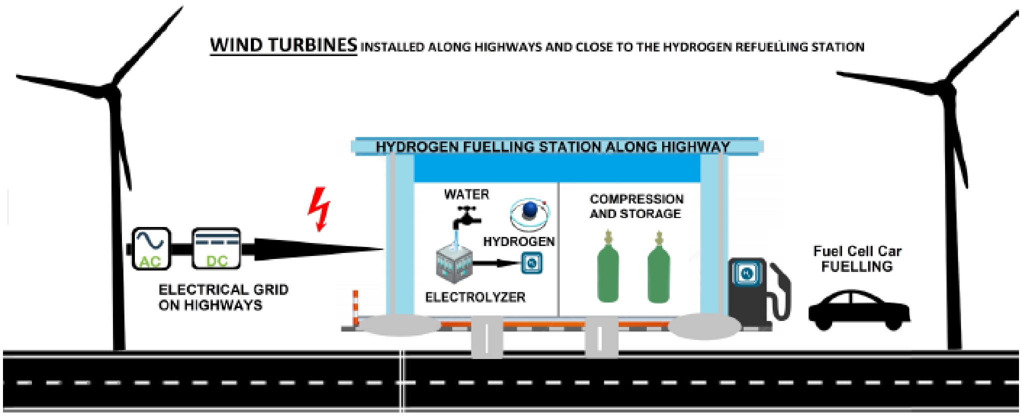
Master Thesis Report

Delft University of Technology

System integration of wind-powered hydrogen refueling station

----- From national level to a case study



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MSc Sustainable Energy Technology
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Challenge the future

System integration of wind-powered hydrogen refueling station

----- From national level to a case study

Thesis study for

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Delft University of Technology

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Cover Picture: on-site water electrolysis hydrogen refueling station powered by wind energy.
from the poster made by Nikolaos Chrysochoidis Antsos
https://www.researchgate.net/publication/315700653_Could_wind_turbines_fuel_up_our_future_hydrogen_refuelling_stations_A_GIS-based_methodology

Abstract

As one of the carbon-free emission transportation method, fuel cell electric vehicles (FCEV) have become a very popular research topic for the recent years. However, as the fuel of FCEV, the hydrogen is usually produced by traditional steam reforming method, which is still not an environmentally friendly process.

This report focuses on the study of infrastructure for hydrogen producing and refueling with zero carbon emission. An on-site water electrolysis hydrogen producing and refueling system powered by wind energy is designed and simulated in this study. The hydrogen produced on-site can reduce the hydrogen delivery cost. The system is also designed to be established via retrofitting the existing petrol station in Germany to reduce the investment cost.

The hydrogen is produced by on-site PEM electrolyzer powered by distributed wind turbine. First of all, the suitable petrol stations for such hydrogen refueling station modification are selected by GIS data analysis in Germany. By applying the constraints for safety and noise consideration, about 500 stations are selected from over 10000 petrol stations in Germany.

Furthermore, the hydrogen producing and refueling system is designed and simulated by MATLAB modelling. The system is composed of five main components: wind turbine, PEM electrolyzer, compressors, storage tank and hydrogen dispenser. The technical and economic details for each of these devices are defined by a series of literature review. Besides, some parameters are from the real commercial products to make the system model more practical.

A case study is built to validate the designed model for a 330kg/day H_2 refueling station in Germany based on both current and future scenarios. The results show that more than 170 tons hydrogen can be produced annually. It can cover most of the hydrogen demand for the refueling throughout the year, which eliminates most of the hydrogen delivery cost from the other producer to the refueling station.

In addition, by using the optimal pre-allocation control strategy, the system can become partially stand-alone with the grid. Only the high-pressure compressor system and cooling system for dispenser need energy supply from the grid, which is less than 1% of the system energy consumption. It means no extra grid reinforcement is needed. The wind energy can be used in a very efficient way. More than 95% of wind energy can be used for hydrogen producing while the other 5% supplies for the compressors as the electricity. The sensitivity research is also performed based on the climate data in a different year, which shows the stable operational behavior for the system.

Last but not least, the economic analysis is carried out based on the case study. For the current scenario, the hydrogen production cost of the system is €6.1/kg and the overall dispensing price is €10.9/kg. It is expensive because the distributed wind turbine and on-site PEM electrolyzer are still costly technologies for now.

However, with the R&D progress of these technologies, the production cost and the dispensed hydrogen fuel cost price for the future scenario will reduce to €2.6/kg and €5.1/kg respectively, which makes the hydrogen a very competitive fuel for the vehicles in the future.

Acknowledgments

Here I would like to express my sincere gratitude to all the people who give me help throughout my thesis.

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1. Introduction

With the increase of fossil fuel usage demand and greenhouse gas emission, the energy insecurity, environmental pollution and climate change have become the serious problem in the world. Nowadays, many organizations and conventions are devoting to deal with these problems such as United Nations Framework Convention on Climate Change (UNFCCC). Based on the Paris Agreement signed in 2016, the increase of global average temperature needs to be limited within 2℃ above pre-industrial level to make a significant reduction for the risk of climate change.[1] Many efforts need to be done to achieve this. This report will focus on the development of FCEV infrastructure for the emission reduction in transports sector.

1.1 EU greenhouse gas emission trends

For the European countries, the greenhouse gas (GHG) emission trends have been made to relieve climate change. According to the report of European Environment Agency (EEA), the long-term target is proposed to be nearly no greenhouse gas emission in around 2050 and the recent goal is to reduce the GHG emission by 20% in 2020 and 40% in 2030 shown in the Figure 1[2].

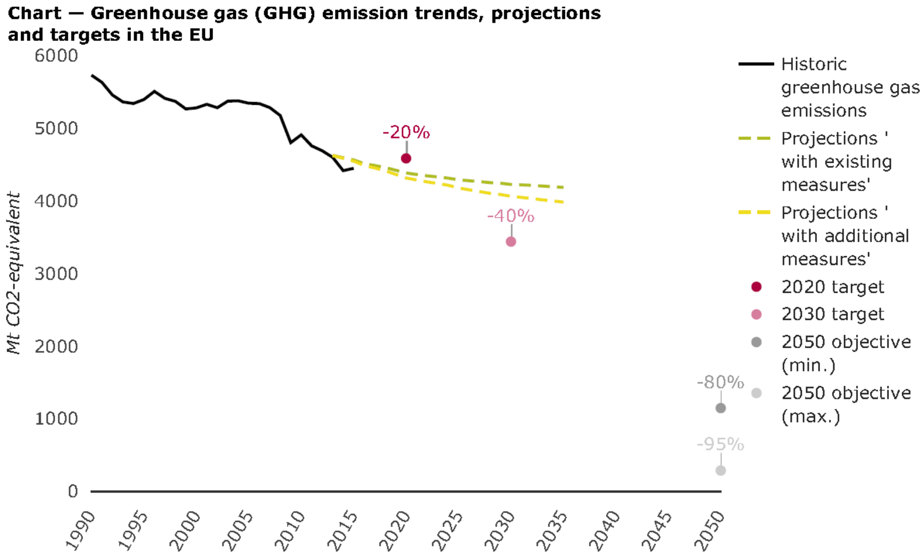


Figure 1 EU greenhouse gas emission reduction target

Although the GHG emission reduction target for 2020 has been achieved, the projected GHG emission will still not reach 30% reduction compared to 1990 levels. The 2030 goal will be achieved only if more clean energy projects are executed in next 10 years.[2]

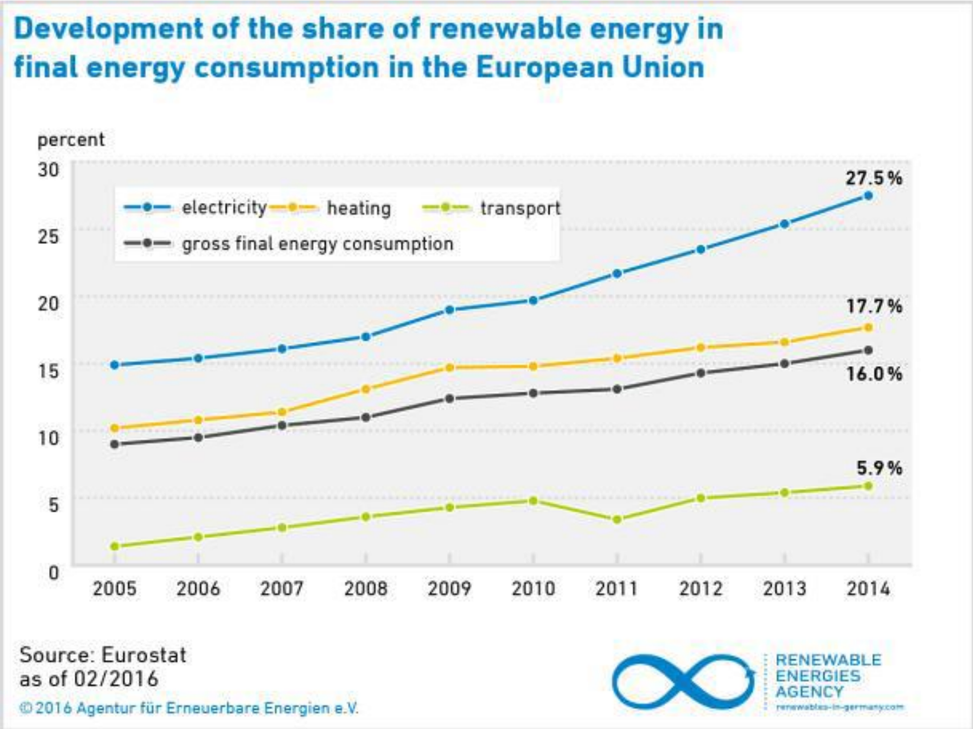


Figure 2 Development of the share of renewable energy in energy consumption for EU

The EUs have a very fast increase in renewable energy usage in various areas shown in Figure 2. Over 25% electricity and 6% transport consumption have been replaced by the renewable resource up to 2014. As the pioneer of renewable energy development in EUs, Germany has an "Energiewende" commitment for transition to a sustainable energy economy who gave a series legislative support for the energy transition to an environmental friendly and affordable energy supply.

1.2 Renewable energy overview in Germany

Because of favorable policy, the renewable energy develops very fast in Germany.

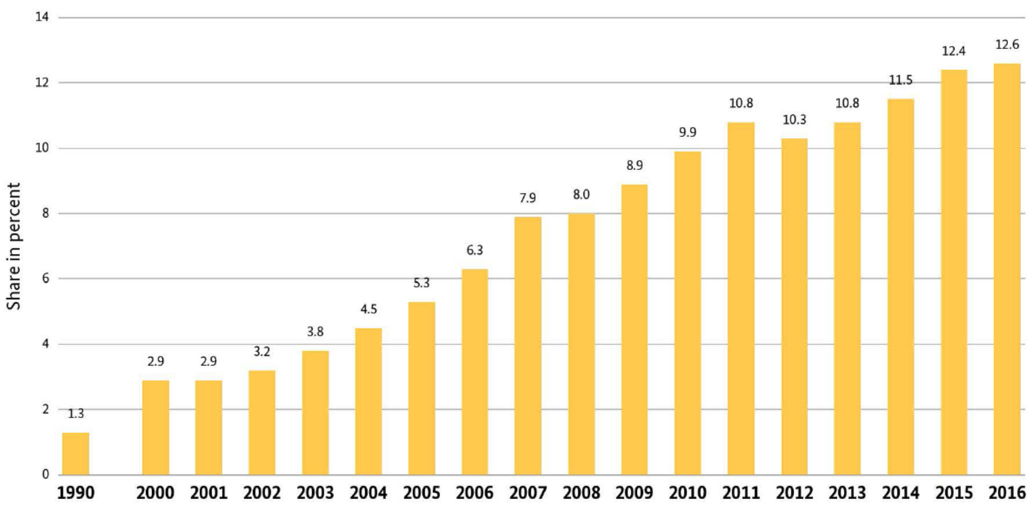


Figure 3 Development of renewable energy share of primary energy consumption in Germany[3]

Figure 3 shows that in the past ten years, the share of renewable in the energy market has been tripled. Because of the R&D efforts in various renewable technologies, many of them have been commercialized successfully, among which the solar and wind energy technologies are widely used for the commercial renewable power plant and distributed system. The price of these technologies have become competitive with the traditional power system and will be lower in the future.[4]

On the view of energy utilization, shown in Figure 4, one large energy consumption sector is transport, which consumes about 30% of the total energy.

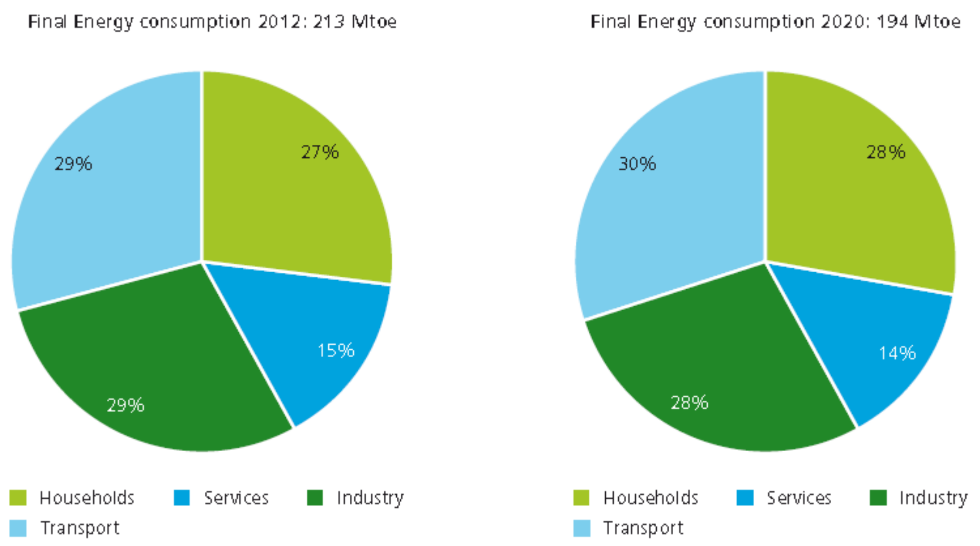


Figure 4 Final energy consumption in 2012 and 2020 target by sector[5]

To reduce the pollution because of fossil fuel used in the transport sector, in 2014, six industrial partners including Shell, Linde etc. founded the joint venture H_2 MOBILITY to develop hydrogen refueling infrastructure. They have made a clear roadmap to build over 400 refueling station in Germany.[6]

1.3 Introduction of related technologies

As the fuel of FCEV, the hydrogen is usually produced by centralized Steam Methane Reforming (SMR) process, which would release a lot of carbon at the same time. This study is to seek a carbon-free method to produce enough hydrogen by renewable energy resource for fuel cell car refueling.

Because of the cost reduction of renewable technologies and popularization of fuel cell electric vehicles (FCEV), many reports indicate the refueling system for FCEV charging will be widely established in the future.

The key technology for this system contains two parts. First is the wind energy production and another part is for on-site hydrogen producing and refueling process.

1.3.1 Wind technology background

The wind turbines have been used for electricity generation for several decades[7]. With the development in manufacture field and R&D progress, the wind energy has become one of economical way for electricity generation. Besides, wind energy is one of the lowest-priced renewable energy resource in today's world with lots of advantages such as small footprint and low running cost.[8]

The installed capacity for wind turbine has a rapid increase in the recent 10 years. Up to 2016, the cumulative installed wind capacity has reached to 480GW, increasing by 20% compared with 2015, and 8% of them installed in Germany which is 4^{th} in the world.[9]

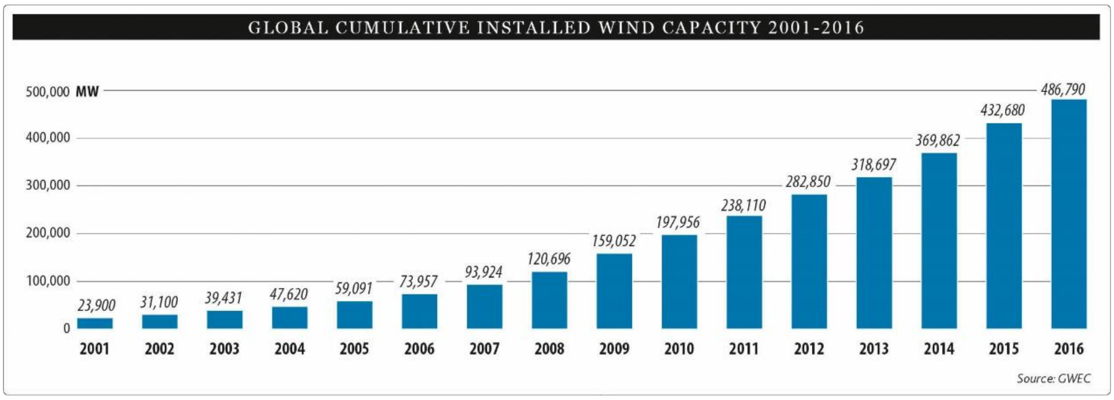


Figure 5 Global installed wind capacity

Therefore, the wind energy is preferred to be used as the energy resource for the hydrogen production. Only one or two large-scale wind turbines can cover all the electricity demand from a medium hydrogen refueling station (500kg/day) and the small footprint makes the on-site electricity production be possible, which will eliminate the cost of long-distance grid construction. The fast development of wind turbine will also reduce the investment of wind project further so that the carbon-free hydrogen can be produced with rather a low cost in the future.

1.3.2 Fuel cell vehicle and hydrogen refueling development

As one of the potential carbon-free energy, using the hydrogen in the mobility field has been noticed and studied for a long time. The hydrogen company Nel[10] already has their hydrogen refueling solution offers all the components for a refueling system including electrolyzer, refueling compressor and dispenser. The electrolyzer manufactured by Nel has a large capacity up to 400 Nm^3/h. The other manufacturers, such as McPhy[11], Siemens[12] and Proton[13], also have their own plan for hydrogen refueling system development.

Furthermore, the wind-powered electrolysis for hydrogen production is also noticed by some companies and research institutions. NREL has already designed and tested a very small electrolysis hydrogen producing system powered by the wind turbine in 2009 (10kW-100kW) and indicated that the resulting hydrogen production cost would be around \$6/kg H_2 (in USD_{2008}). HYDRONICS also develops their own commercial hydrogen refueling station can be powered by renewable energy[14].

To make the future green society, Germany also make many efforts on the emission reduction from the transportation aspect. One of the solutions is using the renewable energy vehicles to replace the fossil fuel cars. H2 MOBILITY project is right for fuel cell electric vehicles (FCEV) that use the compressed hydrogen. Although there are only three types commercial FCEVs sold in the current market[15], this technology has been proved that they are suitable for everyday use in the future.

1.3.3 Distributed renewable energy system introduction

Currently, most of the renewable energy plants or industrial hydrogen production plants are all centralized systems, which have the very large capacity. However, for some rural areas or the place that large grid connection is not available, the distributed system would become the better solution. [16] In this study, the geographic environment is quite various for different stations, so the distributed system should be appropriate for these stations to reduce the cost of hydrogen distribution.

Meanwhile, compared with the centralized system, the distributed system allows for direct private investment for generation and has simple procedures for site permission. It can also reduce the electricity transmission and distribution losses. The system will also have more independence by producing hydrogen on-site.[17]

1.4 Research objective

Based on the background and the state of art about related technologies abovementioned, the study aims to design an on-site hydrogen producing and refueling system powered by the wind turbine. Because the existing petrol stations have a lot of infrastructures that can also be used for the hydrogen refueling station, the investment can be reduced further if the system can be constructed by retrofitting the existing petrol station.

This report is to discuss how to transform the current petrol station into a wind-powered hydrogen refueling station with on-site water electrolyzer system.

The following research questions will be discussed in this report:

- **How many petrol stations in Germany can be modified as the wind-power hydrogen refueling station?**
  - What are the necessary conditions that the refueling station need to meet?
  - How to select the suitable fueling stations to be converted as the wind-powered hydrogen refueling station based on a set of criteria with the help of GIS analysis?
- **What is the design of the wind-powered hydrogen refueling station?**
  - What are the preliminary estimations and assumptions for the technical parameters of the components?
  - What is the appropriate control strategy for the system?
  - How much hydrogen can be produced annually and what is the operation behavior of the system based on the case study?
- **How to identify the economic feasibility of the system?**
  - What is the estimated investment for the system?
  - What is the cost price for hydrogen production and dispensing?

1.5 Outline of the report

The report consists of seven chapters. The current statements for renewable energy development in EU and Germany have been introduced in Chapter 1. Then the state of art for the related technologies are illustrated followed by the research objective and thesis outline. The next chapter provides the filtering methodology to select the suitable location for the system establishment. Chapter 3 then gives the system design and determines all the technical and economic parameters will be used in the simulation model. Chapter 4 explains the detailed control strategy for the hydrogen producing and refueling system. The system and control logic are both tested and improved based on the case study in Germany in Chapter 4.

In Chapter 5, the cost analysis is performed according to the case study. Chapter 6 concludes the study in three aspects: location selection, system design and economic feasibility of the project. The last chapter gives the recommendation for further improvements of the system.

2. National-level site selection methodology for the wind-powered hydrogen refueling station based on GIS database

The basic idea in this study is that the system will be set up by modifying the existing petrol station, which will reduce the cost and difficulty of the system establishment. Then the first step is to find the suitable location for such on-site wind-powered hydrogen refueling station construction. Thus, a selecting methodology should be built for all the stations in Germany to estimate the viability based on several criteria and 5% of the station would be selected out in the end. In this chapter, the way to create and apply such method will be explained and the selection results for Germany will be discussed, too.

2.1 The appropriate criteria for the station candidates

The wind-powered refueling hydrogen system introduced in this report is mainly composed of two parts, the first is the on-site wind-powered hydrogen production system including the wind turbine, electrolyzer and associated device. The second part includes the storage tank, compressor and dispenser, which is also called Compressing, Storage and Dispensing (CSD) system.

To simplify the design difficulty as well as decrease the investment for such system, the study focuses on the possibility to modify the existing fueling station so that some of the infrastructures can be still used for new hydrogen refueling station such as grid connection, the main building, pipeline layout and the other associated systems.

The CSD system only needs enough space to be installed. Since most fueling stations have parking field and available space around, they can be used for CSD system installation.

On the other hand, the on-site wind turbine has more constraints for setting up. Because of noise and safety reasons, many countries have limited the minimum distance between the large wind turbine and the other residential buildings or ecological preservation areas.[18][19] Meanwhile, to maximize the performance of wind turbine, it should be also set in the place away from large obstacles. This kind of distance constraint is also called setback.

2.2 Methodology application in Germany

The methodology will be explained and applied in this section based on the data of Germany. The suitable fueling stations will be located after several filtering steps. These procedures are performed via the QGIS software.

2.2.1 Filtering based on proximity to populated area

Because the wind turbine should not be built near the residential area, the petrol stations near the urban area will be excluded first by using the city network vector data from EuroGeographic database[20]. The study will use the 2014 data in this research[21]

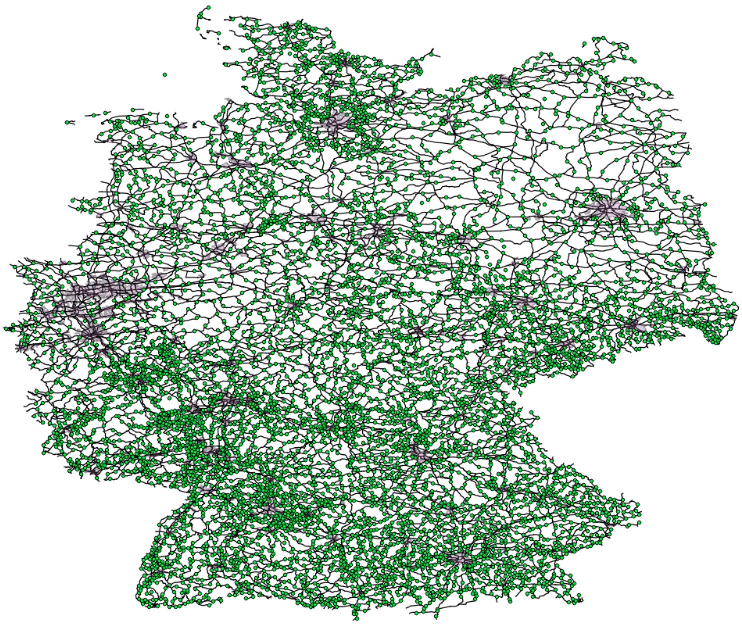


Figure 6 City and road network in Germany

The large cities are represented by the polygons while the small villages are all the point data. First, a setback area should be made to exclude the station near the urban area. This area is made by buffer function in QGIS which can create a circular area with the center of point vector.

The radius of buffers is based on the setback distance for a wind turbine. Both the noise and safety issues should be considered in the model.

For the safety consideration, it protects the other buildings or persons from danger because of ice or blade fragment throw if the failure happens, although it is rare that the fragments happened to hit a person. There are many studies about this setback distance evaluation. [22] gives the setback standard for several Canada provinces. Rogers et al. study the safety distance by dynamic Monte Carlo simulation[23]. Larwood et al. study the same problem with using trajectory model[24]. In the engineering field, the simple and common used formula is shown in below, which is also used in GE design guideline for the safety distance:

$$\text{Setback}=1.5*(\text{Rotor diameter} + \text{hub height}) \ [25] \tag{2.1}$$

That is to say, if a large wind turbine with less than 150m diameter and around 150m hub height, this setback distance should be no more than 500m based on the formula above.

For the noise consideration, the setback standard is various a lot from different countries.[18] In Germany, many states suggest the wind turbine should be 750-1000m away from the residential areas and at least 400m for the solitary house[18]. Especially, Hamburg has published a document to outline the requirement of wind turbine mounting. The turbines should be at least 300m from the individual residence and 500m from the city area. In addition, the wind turbine needs a 50-100m setback from road and railway, and 200-500m away from the forest or the other eco-protection areas for environmental concerns.[26]

In conclusion, the noise setback is usually larger than the safety setback distance, so the buffer distance in the QGIS filtering will be set based on the noise setback. Because of comprehensive consideration of various policies in Germany, the setback buffer for city area (polygon data) is set to be 500m for the city area. For the village points, the buffer radius is 1500m that also account the area of these villages themselves.

The map after applied all the buffers for setback is shown below.

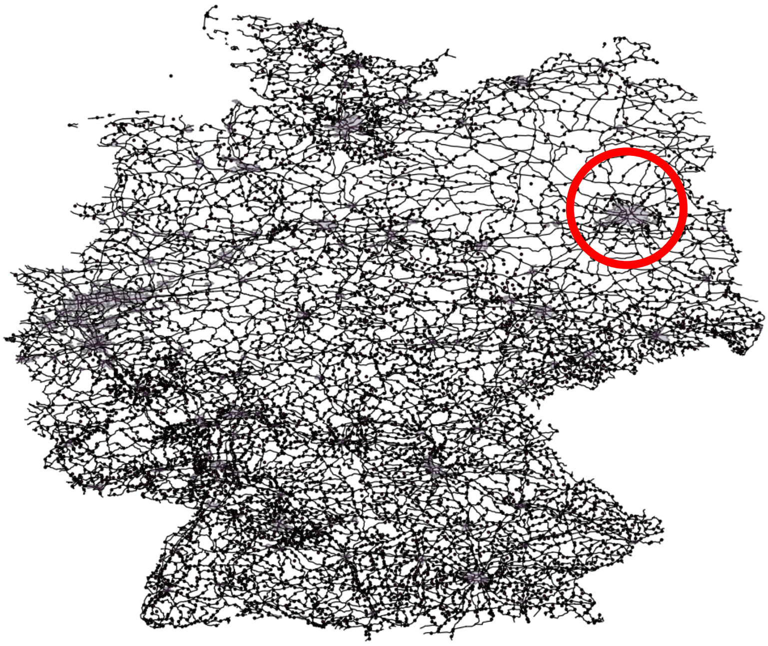


Figure 7 The network map with noise setback buffer

Zooming in the map to Berlin for a clearer view is shown in Figure 8.

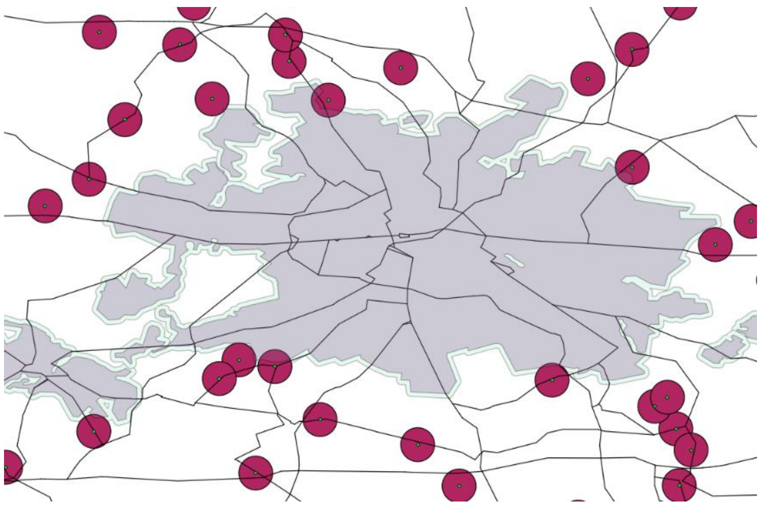


Figure 8 Regional network map with noise setback buffer near Berlin

The green points are the location of small towns and grey areas are represented for the large urban areas. The buffers are applied in the map, which are the scarlet areas for small villages and light grey region for city areas.

Then all the fueling stations in Germany are illustrated on the map according to the investigation from GPS Data Team[27]. There are 10518 fueling stations marked on the Germany map with a violet point.

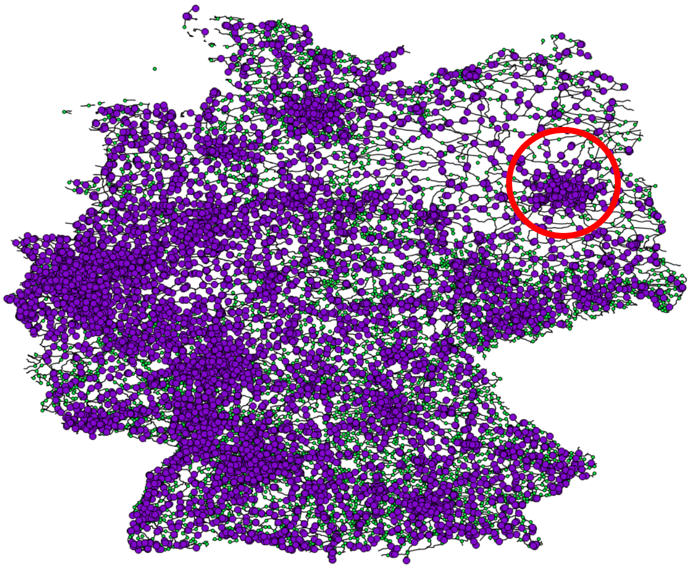


Figure 9 The map of fueling station in Germany

Similarly, zooming in the map to Berlin as the template is shown in Figure 10. (The region in the red circle on Figure 9).

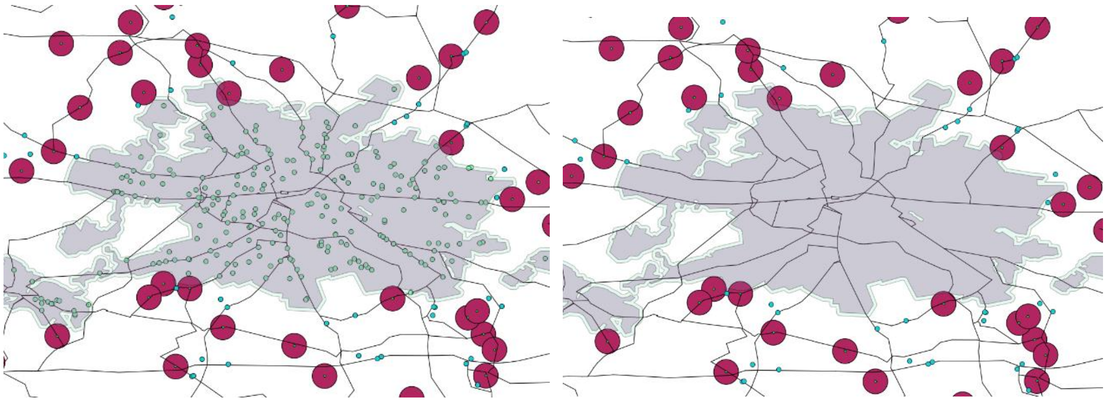


Figure 10 The station before and after the noise setback filtering

Figure 10 shows the map before and after the setback filter applied. All the stations in or near the urban area are excluded after this filtering process. As a result, 2998 stations are left after first filtering, which means about 70% of the stations are built in or near the urban areas.

2.2.2 Filtering based on the land use

The land use filter is used to exclude the station near some special nature or artificial area. The airport and ecological protection zones are considered in this step.

The aviation department requires extra distance because the wake generated by the wind turbine will impact the aviation devices[28], this distance is not ruled clearly but defined by the aviation department individually. However, there is evidence that the wake generated by the turbine can be recognized up to 2000m of downwind side[29]. In this study, a buffer with 2000m distance is applied to filtering out the station within this area.

Additionally, the on-site wind turbine should also be about 500m away from the eco-protection area[26]. The location of these areas are derived from the land cover and land use database LUCAS updated in 2015[30]. In this database, the ecological area is divided into for protection and for hunting. The filter will include both two types. Since the location is recorded as the point vectors, considering the area for these zones themselves[31], a buffer with 2000m distance is created to exclude all the station in it.

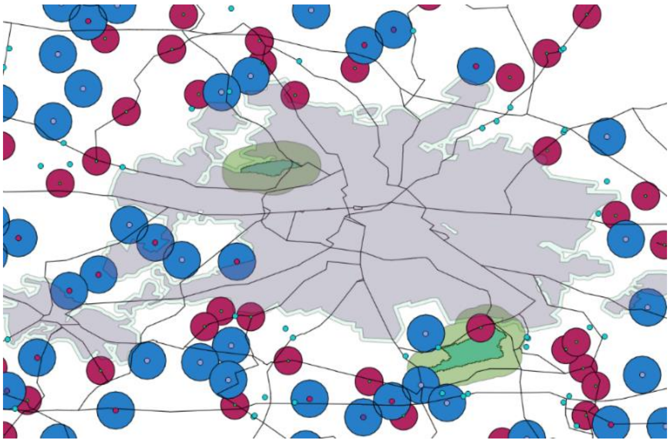


Figure 11 The map with more buffer for airports and protection zones

All the buffers and points should be marked on the map. As the Figure 11 shown, the green areas indicate the airport areas (deep green) and the related buffer (light green). All the ecoregions have the blue buffer area, and different center points represent the different utilizations (for protection or for hunting)

The station in these buffer areas will be excluded from the available stations. The comparison before and after this procedure is shown in the figure below.

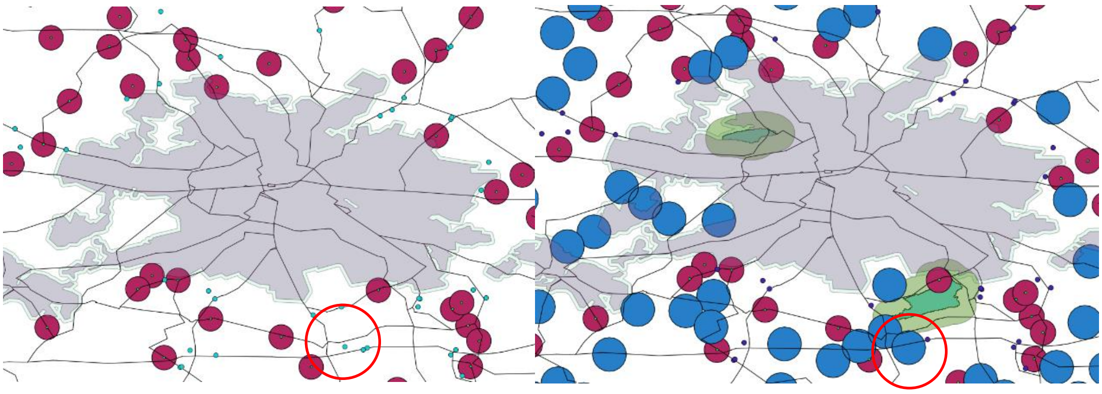


Figure 12 The selected station before and after second filtering

After this process, 2577 station is remained out of 2998, which means only about 15% stations are excluded because of environmental and aero concerns.

2.2.3 Filtering based on the land cover

The previous filters only concern to avoid the populated areas and special land use areas. The land cover condition should be also identified since the wind turbine need to be set in an open area with fewer obstacles around where more wind energy is available. Generally, the wind turbine should be constructed on the solid land structure that can support the foundation and turbine. It should also not be installed near the special landscapes such as forests, railway or inland water.[19] To select out the suitable area, a more detailed land cover data is required. Thus, the raster data from the CORINE Land Cover (CLC) database, which is updated in 2012 with a refined raster map (geographic accuracy better than 100m) including over 40 types of land cover classes.[32]

However, this data cannot be used for filtering directly since it is raster while all the other data are vectors. Some preliminary works should be done first. Still, the QGIS software is used as the developing tool.

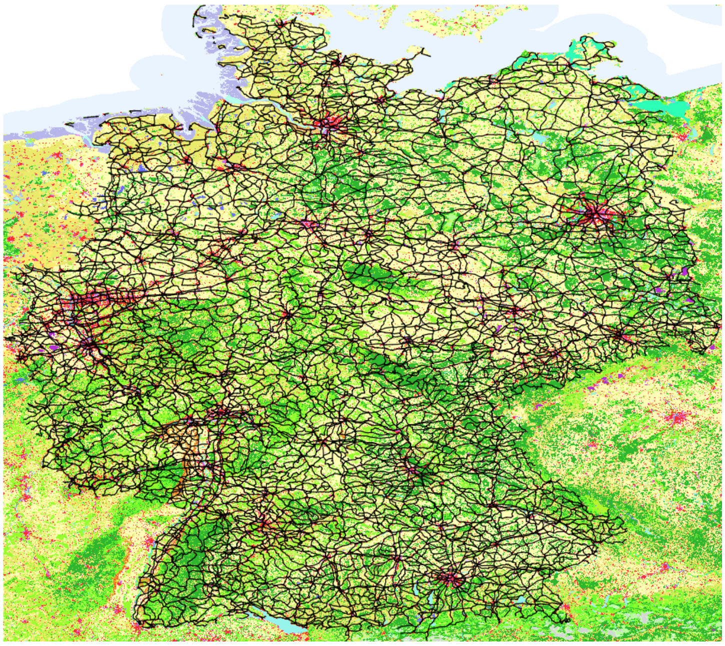


Figure 13 The land cover map in Germany area

The raw data from CLC includes all the European countries, so first cut it and leave the Germany part only based on the coordinate shown in Figure 13. The road network is also illustrated to show the Germany territory boundary. The different color pixels are referred to the different land cover types, which means the land cover type is distinguished by unique RGB value.

The table in Appendix A lists all the 44 classes used in CLC and their RGB values, notice that some of class may not appear in the Germany map such as Sclerophyllous vegetation (RGB code 166-230-077).

The raster data is then converted into polygon data via some data processing methods by both QGIS and MATLAB. The polygons are classified by different land cover types and drawn on the same map.

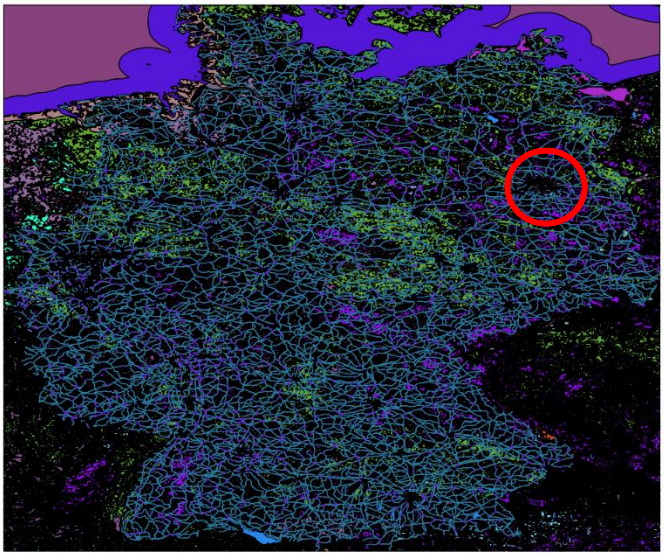
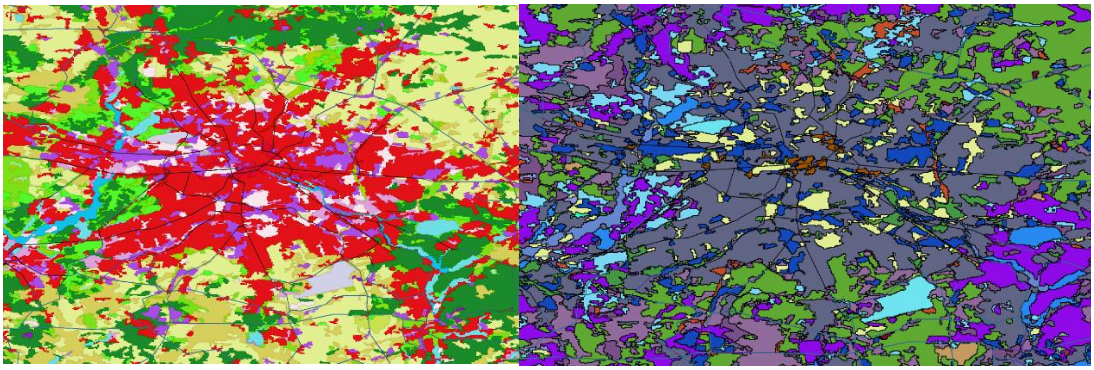


Figure 14 The polygon map for Germany land cover

It seems that the polygon data looks deeper because there are lots of polygons with black boundary lines. Zooming in the map for just the region of Berlin (red circle in Figure 14) in Figure 15 shows that comparing with the original raster data, the features of new vector map is not changed.



Raster data **vector (polygon) data**

Figure 15 The comparison of raster and polygon map for the Berlin region

After this preparation work, the suitable land cover types are chosen for the filtering. The National Renewable Energy Laboratory (NREL) studies the land-use requirement for wind power plants and gives the distribution of wind energy plants on different predominated land cover types. It indicates that the wind plants prefer to be established on the grass or crop land while there are fewer wind plants built on the forest land, which only shares 6.5% of the projected capacity.[33] The desirable types for wind turbine installed in the model include several agriculture or vegetated land classes, pastures, grassland and dump sites. All the selected types are highlighted in the table of Appendix A

In this step, all the station within the selected region will remain and the other station will be removed since the system should be built on the suitable land cover location.

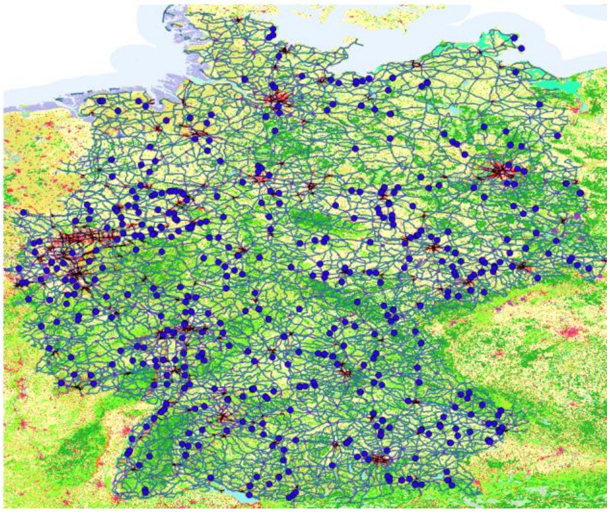


Figure 16 The suitable fueling station in Germany after the third filtering

Figure 16 illustrates all the suitable station location (blue point) after this step. Only 525 stations are chosen from 2577 station, which means about 5% of the fueling station is suitable to modify as the wind-powered hydrogen refueling station according to the geographical conditions.

2.2.4 Filtering based on wind resource

Besides the geographical condition, another very important factor for the wind power system is the wind condition. The wind resource classification is based on IEC 61400-1 standard[34] and will be used for wind turbine choice. And the main factor is the annual average wind speed at hub-height shown in the table below.

Table 1 Wind speed classification [35]

Wind class - Turbulence	Annual wind speed at the hub height (m/s)	Extreme 50-year gust in meters/second (miles/hour)
Ia High wind - Higher Turbulence 18%	10	70 (156)
Ib High wind - Lower Turbulence 16%	10	70 (156)
IIa Medium wind - Higher Turbulence 18%	8.5	59.5 (133)
IIb Medium wind - Lower Turbulence 16%	8.5	59.5 (133)
IIIa Low wind - Higher Turbulence 18%	7.5	52.5 (117)
IIIb Low wind - Lower Turbulence 16%	7.5	52.5 (117)
IV	6	42.0 (94)

To determine the wind resource class in different place, the reanalysis wind speed data for past ten years (2000-2010) is used. It is derived from The European Centre for Medium-Range Weather Forecasts (ECMWF) public datasets[36]. It collects wind speed reanalysis data at 10m and 100m, but the hub height of applicable wind turbine in this study is about 150m. The wind speed needs to be converted into hub height first according to the wind speed conversion methods, which is explained in Appendix B in detail.

Figure 17 shows the wind speed distribution in Germany, the speed of north part is much higher than the south part since there is abundant wind energy resource around the offshore area.

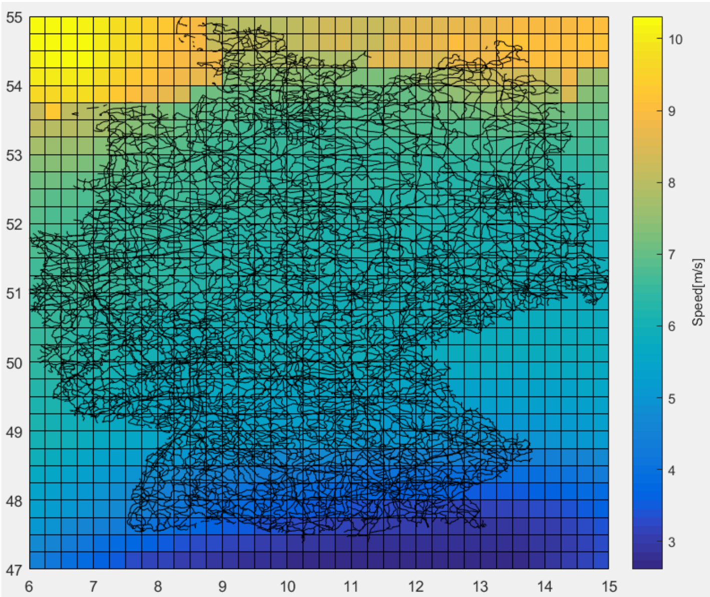


Figure 17 Wind class map for Germany

However, most part of Germany territory is inland so that the wind speed is around 5.5-7 m/s which means it belongs III or IV classes. Then the station distribution based on the wind class can be derived, which will be used for wind turbine selection.

For example, filtering all the stations drop in the class IV area is illustrated in Figure 18.

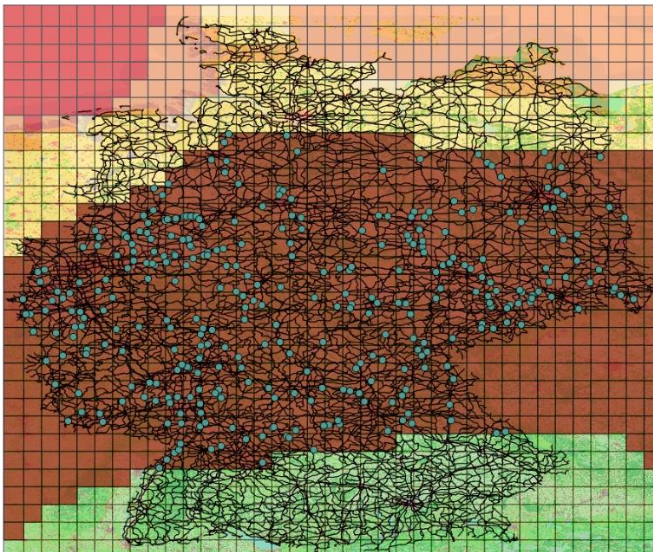


Figure 18 The fueling stations only lies in Class IV

There are 378 stations in class IV, which means the average wind speed is 5.25-6.75 m/s in this area. Based on this filter, the wind energy production can be estimated for the system sizing.

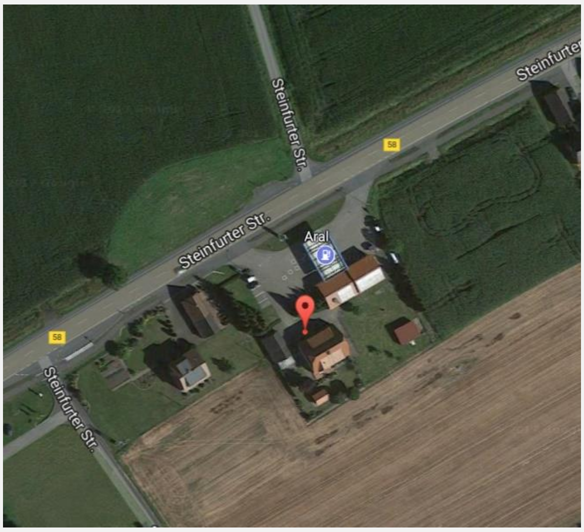
2.2.5 Alternative filtering

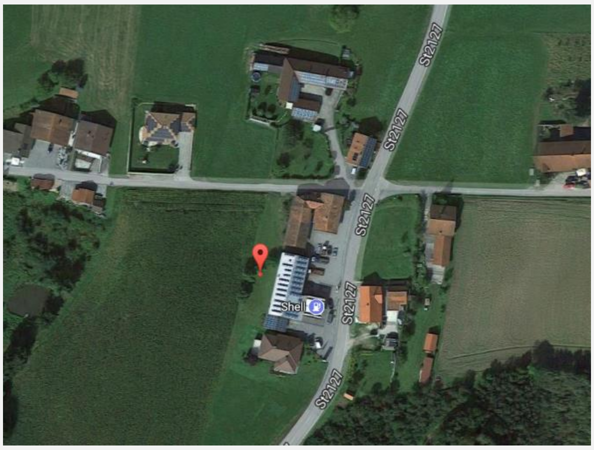
After these filtering procedures, the stations satisfied the geographical conditions and policy constraints can be picked up. And the system scale estimated based on the wind resource quality can be also derived based on the result after wind condition filtering.

Moreover, some alternative filtering can be applied if there are more requirements for the system establishment. For instance, the investors also concern about the traffic density near the station in order to estimate the demand. Then a filter to classify the stations based on the road type nearby can be created for this task.

The appreciated 'nearby' road is defined as the one within 250m away from stations. The EuroGeographic data base has already classified the road as "primary route", "secondary route", "national motorway" or "local route"[21]. The results are shown in Table 2.

Table 2 The summary of the station number after every filtering

Road Type	Number*	Example in Google Map
Primary Route	**195**	 **(7.64959E,51.8000N) (ARAL)**
National Motorway	133	 **(9.64095E,49.20651N) (ESSO)**

Secondary Route	68	 **(13.30348E, 48.6833N) (Shell)**
Local Route	7	 **(13.39461E,48.87718N) (Shell)**
Unclassified	165	These stations are not near any roads that are recorded by the GIS data (CLC database).
Total	525	

***One station may be accounted for several times as there may not only one road near it. So, the total station number is not merely equal to the sum of all classes.**

There are about 360 stations near the road network. Most of them are built beside the primary route or national motorway. And many of them have more than one road nearby. Table 2 also indicates that the methodology performs rather good for a station near the motorway and primary route selecting. For the stations near the secondary and local route, since the CLC database cannot show the tiny populated area with just several houses, there would be some solitary building near the station.

On the other hand, 165 stations are unclassified since they are not near any roads that are recorded by the GIS database. However, it does not mean the station is in the very remote place. They may near a country road or the road nearby is built recently. By using the more updated and fined database, these stations would be also classified, too. (The issue is also discussed in Recommendation part)

2.3 Chapter summary

In this chapter, a selecting methodology is established based on several filters. The purpose of these procedures is to pick out the fueling station that is suitable for wind-powered hydrogen refueling station modification in a national region scale. The criteria involved in the result include the land use/cover condition and the wind condition based on the technical and political requirements. Then the method is tested for the stations in Germany. The results indicate that about 5% of the station in Germany territory is suitable for modification.

Despite the first three main filter step, there are also many customized filters can be applied according to the different requirements for the project. The section 2.2.5 shows one self-defined filter example to classify the stations based on the road type nearby.

Table 3 gives a summary of the results after applying these filters.

Table 3 The summary of the station number after every filtering

	Before	After
The filter based on populated area	10518	2998
The filter based on land use	2998	2577
The filter based on land cover	2577	525

Generally speaking, such theories can work for any place. The usable scale can be from one district to the whole country. Since most of the databases (EuroGeographic, CLC, ECMWF) used in the model include all the information of all European countries, the filtering methodology can be realized easily for the other region in Europe only if the fueling station coordinate is known. Since making a carbon free or low carbon emission mobility has been the target of EU which means to popularize the clean transportation ways including FCEV, this methodology will make great help to establish the infrastructure of hydrogen refueling system.

However, comparing with the Google Map, the methodology sometimes cannot figure out the stations near the very tiny populated area because of the resolution limitation of the GIS database. Besides, the stations at the edge of the urban area can hardly be excluded by the methodology because the 'data point+circular buffer' excluding area described in Section 2.2.1 and 2.2.2 cannot exclude the station located near urban fabric which has an irregular shape. In Chapter 7 the report also gives several solutions to improve the accuracy of the GIS filtering methodology.

3. Wind-powered hydrogen refueling system design

After finding the suitable location for the system, the next question should be how to design a suitable system for the hydrogen refueling and what strategy should be applied so that the system can fulfill the daily refueling demand for the station. The following two chapters will introduce the system components determination and control strategy development based on the specific case study.

Two scenarios based on current state and the forecast for the future are presented in this Chapter. The cost is based on the facts around 2017 for current scenario and the future cost forecast is based on the prediction for around 2040. Some of the components lack the detailed information for future prediction, so the forecast for around 2020-2025 is used for the future scenario analysis.

Although the device performance and cost have many references for the present situation, the prediction for the future is quite uncertain and have some distinctions from different research groups or different forecast models. Thus, for the future scenario model in this report, all the parameters are assumed to be the results from several references.

3.1 System overview

The objective of this system is to produce hydrogen on-site by wind power and fuel the FCEV via the refueling system. So, the system is actually composed of hydrogen production system and hydrogen refueling system. The production system including the wind turbine and electrolyzer is responsible for converting wind energy to hydrogen. The refueling system is for hydrogen compressing, storage and dispensing which is also called the CSD system.

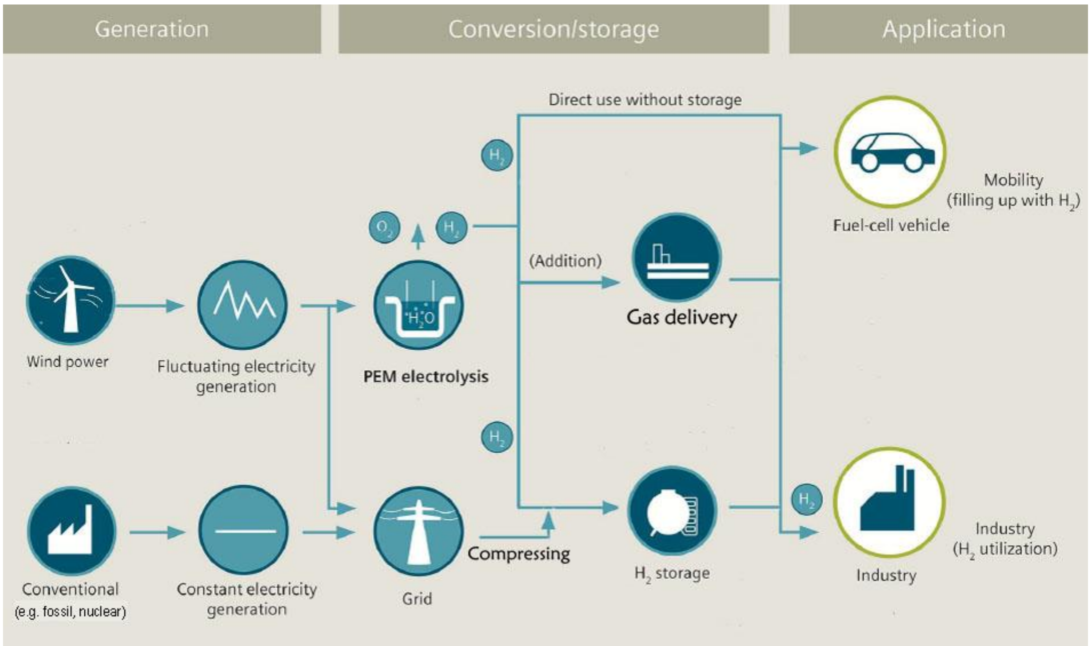


Figure 19 The schematic of hydrogen production-to-utilization flowchart[37]

A schematic of the system is shown above and it is referred to Siemens hydrogen industrial market prediction. The electrolyzer is powered by the fluctuating electricity generated by wind turbine. The produced hydrogen can be stored or delivered for mobility or industrial utilization. Since the wind energy is non-dispatchable due to its fluctuating nature[38], the grid connection is necessary to deliver the excess energy from wind turbine to the grid and supply stable power to the other electrical devices in the system when the wind energy is not enough. Two compressors are used in the system. One is for storage and delivery; the other one is for the refueling process.

3.2 System components determination

In this section, the selection of system components is discussed. The model of each component is defined based on both scientific analysis and commercial product specification from the present market. The model is established based on the energy balance and hydrogen mass balance.

The energy consumption for electrolyzer and compressor is assumed to be constant which is defined by rated capacity or maximum energy consumption, although it should vary according to the inlet and outlet pressure in the actual situation.

Regarding the economic modelling, especially the impact of inflation, all the values have been converted in 2017 USD ($\$_{2017}$), and converted into Euro in the summary section Table 7[39]. And \$1=€0.9 will be used for the estimation

3.2.1 Wind turbine

The wind turbine is an essential system for the hydrogen production system. It converts the wind energy into electrical energy. For the wind energy powered system, the primary criterion is to produce enough energy to meet the daily electrical demand being consumed by the components of the hydrogen producing and refueling systems.

Although there are many wind turbine manufacturers in the world, the product is referred to Vestas and Enercon to build the wind turbine model as they hold a dominant share of the market sales in Europe. The table in Appendix C summarizes the major commercial products from these two companies and their main parameters.

Considering the wind resource distribution derived before (in 2.2.4), the most part of Germany inland is in class III and class IV, which means the wind turbine for high wind class is rarely seen (19 stations near the coast). Thus, the one that can operate under class II or below will be the potential choices for the system shown in Table 4.

Table 4 Potential wind turbine types for the system

Type	Rotor Diameter (m)	Hub Height (m)	Rated Capacity (MW)	Available Wind Class
E-126 EP4	127	99/135/159	4.2	IIA
E-141 EP4	141	129/159	4.2	IIIA
E-103 EP2	103	98/138	2.35	IIIA
V136-3.45MW	136	82/112/132/149	3.45	IIIA/IIIB
V126-3.45MW	126	87/117(II) 137/147(IIIA)	3.45	IIA/IIB
V100-1.8/2.0MW	100	80(IIB)/95(IIIB)/120(IIIA)	1.8/2	IIIA-S
V90-1.8/2.0MW	90	80/95/105	1.8/2.0	IIA/IIIA

The refueling system should be able to supply all the demand from wind energy. The estimated daily demand for the hydrogen refueling station is assumed to be 330kg/day according to the investigation of current petrol station demand and the prediction for FCEV market share. (This is explained in Chapter 4 in detail for the case study.) Considering the efficiency of the electrolyzer and the consumption of the other components, a large wind turbine is preferred for this system. Besides, the turbine should be capable of operating under the low wind speed condition. Therefore, the 4.2MW wind turbine applied for Wind Class III, E-141 EP4, is used for wind turbine modelling in this research.

E-141 EP4 is a customized solution in the 4MW segment for the inland low wind sites. It has the high hub height (159m) and large rotor (141m) to increase the annual production.[40]

Figure 20 E-141 EP4 wind turbine manufactured by Enercon

The power output can be estimated by the power curve of this wind turbine type. The wind turbine model can calculate the hourly electricity production based on the wind speed at the hub height via this power curve. Although the Enercon website already has the power curve plot[41]. The data from wind-turbine-model.com is used because they have the discrete point data on the curve in detail, which is helpful for a more accurate model establishment.[42]

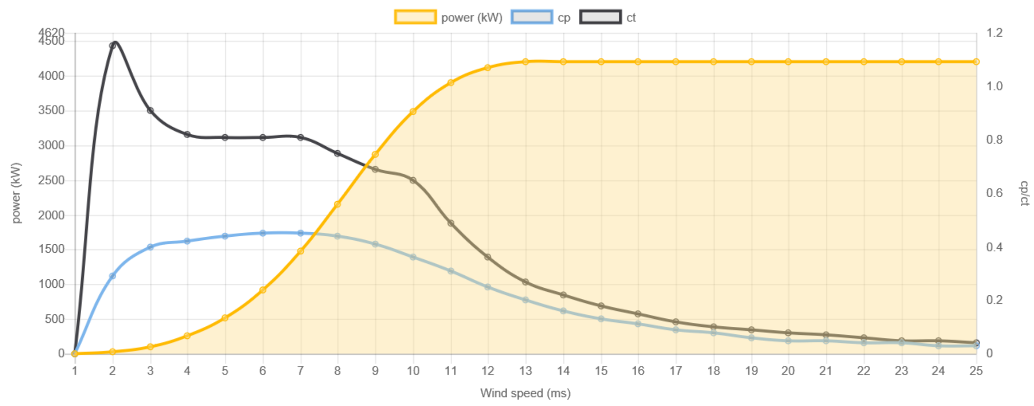
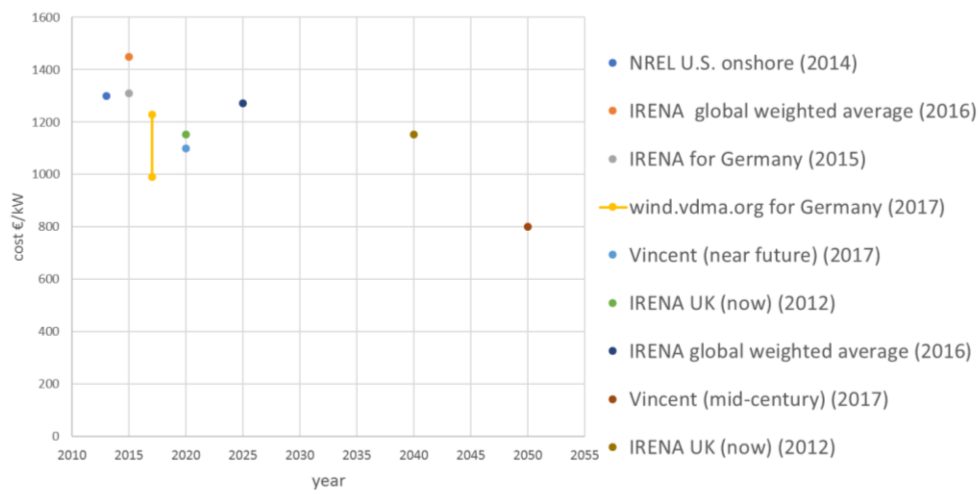


Figure 21 The power curve of E-141 EP4 wind turbine

The power curve shows a low cut-in wind speed (3m/s) and the rated wind speed is 14m/s. It means the wind turbine can have a quite good performance under the low wind speed condition. The study assumes that the electricity output based on this power curve does not employ the energy losses because of the other electrical device in the system, so a 4% loss is set for converter[43], 2% for the transformer[44] and extra 1% for miscellaneous losses such as lights or cables. In short, the efficiency 93% is applied to the electricity output of wind turbine.

For the capital cost of wind turbine, NREL reports the capital of wind turbine in U.S. is in the range from $1442 to $3280 per kW in 2013[45]. For the worldwide market, several reports are published by International Renewable Energy Agency (IREA). A most recent study[4] in 2015 gives the global weighted average installation cost as $1609/kW for now and $1413/kW for the future (2025), which predicts a 13% reduction up to 2025. Although the lowest cost is forecasted as $1281/kW in UK for small-scale wind farm project in 2020 and $1100/kW in 2040[46], the conclusion for wind turbine capital presented in the IRENA report for Germany is about $1456/kW. Besides, wind.vdma.org also reveals that the wind installed capital in Germany is €990-1230/kW for 2016-2017[47]. A study done by Vincent et al. shows the wind turbine cost is €1100/kW in 2020 and €800/kW in around 2050[48]. The cost investigation is summarized in the following figure.



*** The number in the bracket indicates the publishing year for the reference.**

Figure 22 The cost survey and estimation for wind turbine

With the comprehensive consideration, €1100/kW is assumed to be the current installed capital in the model. The future cost is estimated to be €800/kW in future as the optimistic assumption. For the annual O&M cost, although from the study [48] it can be as low as €30/kW, the wind turbine in Germany always has a higher operation cost, which is $67-77/kW from IRENA report[4][46]. A survey from reference[47] shows the cost is about €56/kW. So it is assumed to be €60/kW for now and has the same reduction rate as the capital in the future.

3.2.2 Electrolyzer

Another important component of the system is the electrolyzer. It converts the electricity to hydrogen. There are many kinds of technologies for water electrolysis, among which the alkaline and proton exchange membrane technologies are dominated commercial electrolysis method.[49] The schematics of these two electrolysis concepts are shown in Figure 23.

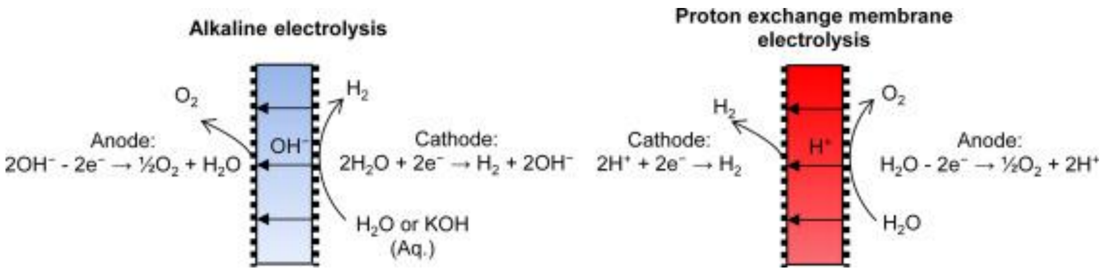


Figure 23 Two main electrolysis principles[50]

Although the PEM has a relative higher overall efficiency and low operating cost[49][51], the high capital cost of this type of electrolyzer makes it not very economically feasible for industrial utilization in the past. However, the recent R&D progress has reduced the material cost a lot, which makes the PEM electrolyzer more competitive with the Alkaline electrolyzer.

In this research, the PEM electrolyzer is applied in the technical model for the refueling system since it is more suitable for the high-pressure refueling system[52] and the cost will have a significant reduction in the future according to many reports[53][54].

The technical parameters in the model are referred to the real commercial PEM electrolyzer.

Figure 24 SILYZER 200 electrolyzer from Siemens [12] **and Proton M series electrolyzer**[55]

Siemens has their own hydrogen solution project called SILYZER[12], in which they develop the PEM electrolyzer for hydrogen production shown in Figure 24. The overall efficiency is from 65-70%. Rated capacity is 225Nm^3/h (The density of hydrogen at standard condition is about 0.09kg/m^3, so the rate production rate is about 20kg/h). This electrolyzer can use the tap water directly with long stack lifetime and very quick dynamic response.[37]

Moreover, PROTON also develops the project for hydrogen refueling solution[13]. Proton M series are the electrolyzers for large scale production. Its net production rate can be 104-417 Nm^3/h based on different types, with overall energy consumption of 59kWh/kg H_2. It can also operate with a very fast response but may need extra water purification equipment.[55] Given that the HHV of hydrogen is 141.88MJ/kg, the overall efficiency of this type of electrolyzer is 66.7%.

The following table gives a summary of main technical parameter for these two types of electrolyzer.

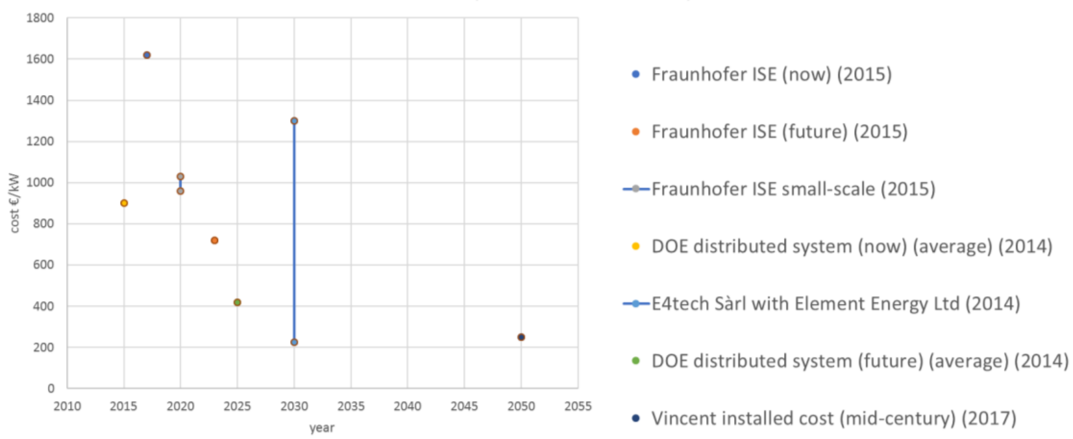
Table 5 The main technical parameters for two types of electrolyzer

SILYZER 200[12]		**PROTON M200**[55]	
Electrolysis type	PEM	**Electrolysis type**	PEM
Rated stack power	1.25MW	**Rated system power**	1.1MW
Dimension	6.3*3.1*3.0m	**Dimension (only H2 gas management part)**	3.3*0.5*2.1m
Start-up time (from stand-by)	< 10 sec	**Start-up time**	<5 min
Output pressure	Up to 35 bar	**Delivery pressure**	30 bar
Rated H2 production	225Nm^3/h	**Rated H2 production**	209Nm^3/h
Overall Efficiency (system)	65-70%	**Power Consumption by production**	59kWh/kg (66.7% in equal)
Tap Water Requirement	1.5L/Nm3 H_2	**Water inlet flowrate**	373L/hr (1.7L/Nm^3 H_2 in equal)
Design Life Time	>80000h	**Water needs to be purified**	ISO 3696 Grade 2 Deionized Water required

In the simulation model, the basic parameter is the efficiency of electricity-hydrogen conversion. The study will use a constant overall efficiency/ energy consumption including the purification energy consumption according to the technical data from these manufacturers.[12][55] The overall efficiency of 67% will be used in the model for the current state. In the future, since the forecast is 71% for 2025[54] and the large-scale electrolyzer is predicted to be 77% in 2030[56], the efficiency for small scale can also reach 75% for the future scenario. The rated capacity and the other parameter will be determined by the local condition and demand. Since the lifetime of the stacks is over 80000h shown in the table above, only some stacks are assumed to be replaced for now. In the future, as some reports have already claimed, the lifetime can reach 90000h[57]. The study assumes no replacement is needed during its lifetime. The tap water consumption is assumed to be 1.5L/Nm^3H_2 according to the SILYZER, which is 16.67kg water/kg H_2.

For the cost aspect, the references are from the study about distributed PEM system (less than 5 MW). Department of Energy (DOE) reports a \$800-\$1200 uninstalled capital cost associated with 10-25% installation cost factor[54], which is around \$1000/kW in average for 2015 target. Report [56] gives €960-€1030/kW for a 2020 project and €1620/kW for the small scale electrolyzer by now. With the R&D progress, the future cost of electrolyzer will reduce a lot. According to the study for Europe market[57], it will be in the range of €255-1300/kW in 2030. DOE also reports it will be

$467/kW in average for 2025. The optimal forecast says the capital for electrolyzer can be reduced to as low as €200/kW in 2050[58]. Besides, the research from reference [48] gives an installed cost of €1790/kW for now and €250/kW in the future.



*** The number in the bracket indicates the publishing year for the reference.**

Figure 25 The cost survey and estimation for electrolyzer

After considering all these references, the installed cost in this model is assumed to be €1200/kW for the current scenario with 15% extra cost for replacement[53] and €250/kW with no replacement for the future scenario. The O&M is set to be 2.5% of the investment based due to the conclusion from [57] and [48]. The installation cost is 12% for now and 10% in the future[48].

3.3.3 Storage tank

The hydrogen needs to be stored after being produced, so there needs some stationary storage tank on-site. Specifically, there are two kinds of storage tank fixed in the refueling station. One is for storing a large amount of hydrogen with low to medium pressure, while the other one is for refueling with high pressure[59], which is also called cascade.

The Type I or II vessels are usually used to be the storage tanks with low pressure. This is a mature technology to use the steel vessels keeping the compressed gas. R&D process is focusing on the new material or composition research, which can reduce the cost of tank as well as overcome higher pressure.[60] In the model, two 200bar tanks are used for on-site hydrogen storage with 400kg capacity for each. One additional tank is used as the backup tank, which can be assembled with the truck trailer and thus be traded via the hydrogen network. The capacity of storage tank can be varied based on the available space at the station. In order to match the mobile backup with the stationary tank, 400kg is used based on the minimum tube trailer size[61]. There is an additional discussion about the economic impact because of storage tank capacity in Appendix D, from which the study indicates that the small capacity tank is more suitable for the system.

Both DOE and NREL forecast the cost reduction and pressure increase for such stationary tank.[59][60] In the future, the storage pressure will increase to 400bar in order to store more hydrogen with a small area occupied.

Figure 26 Pressure vessel (transportation is available) (from Google picture)

The hydrogen in the storage tank will be further compressed and stored in the cascade first. When there is a refueling request, the dispenser will draw the hydrogen from cascade directly and fuel the cars. Since cascade is the temporary storing container for dispensing preparation, many companies, such as Linde and McPhy, integrate the high-pressure compressor, cascade, cooling and dispenser device together for their hydrogen refueling solution.

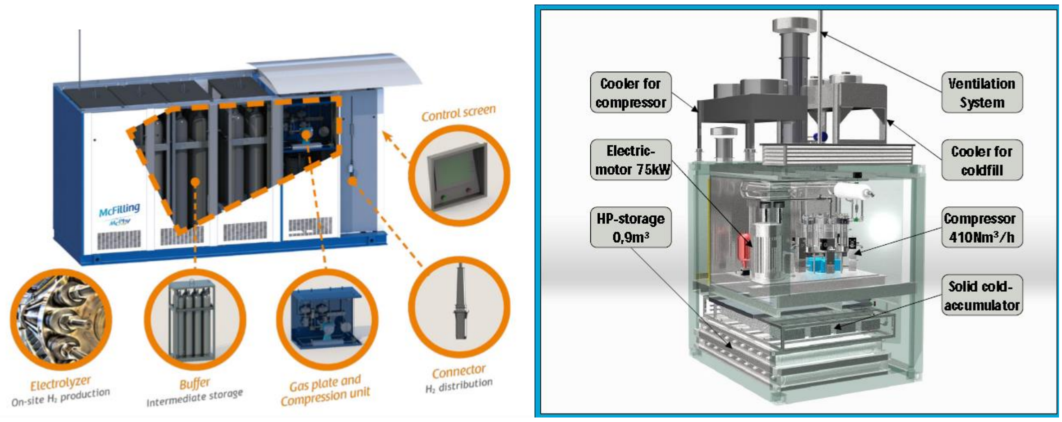


Figure 27 Compact refueling system from McPhy and Linde

The capacity of cascade will be modelled according to the demand. The rated pressure should be higher than the dispenser pressure. Nowadays, most of FCEV is fueled based on SAE J2601 standard[62] with 70MPa, the cascade pressure can be 90-100MPa. The model is based on the technical information from Linde, so it is set to be 100MPa.[63]

Since there is less information for the cost of compact system study, the price of the cascade is evaluated based on the study of the normal high-pressure tank. Nowadays, many surveys indicate that the cost of both low-pressure and high-pressure tank have already achieved the DOE target for 2020, which is $800/kg for low-pressure and $1100/kg for high one[59][60]. There is even lower price for a low-pressure tank that is around $750/kg[64]. In the future, the stationary tanks will be upgraded to the medium-pressure tanks (around 400bar). DOE gives a prediction that the ultimate cost for medium and high-pressure tanks with small capacity can be $690/kg[65], and the study for composite tank shows the possibility for very low tank cost[60]. For small capacity high-pressure vessels, DOE estimates that the cost can be as lower as $460/kg according to the manufacturing capacity[66].

Therefore, €675/kg and €990/kg are used for the two kinds of tanks in the current scenario based on an optimal assumption. For the future scenario, the cost for the medium-pressure tank can be as low as €420/kg for storage tank referred to the medium pressure tubes cost from the relative study by Vincent[48]. €510/kg for cascade is assumed based on the average value of survey above. In addition, the O&M cost according to Vincent's study is 1% of the investment per year and the lifetime is long enough without replacement.

3.3.4 Compressor

The hydrogen would be stored in the stationary tank after produced. These tanks have large capacity with low or medium pressure, so the hydrogen should be compressed to fill the tank. Thus, the system needs a low or medium pressure compressor to finish this job.

On the other hand, the hydrogen needs to be compressed to very high pressure (90-100MPa) before fueling to the vehicles. To achieve this, another high compressor is applied. It can compress the hydrogen from the storage tank for refueling.

There is less evidence about the operation efficiency from the commercial products. But many studies report that the isentropic efficiency of current compressor should be 65% and it will increase to 80% in the future [59][67]. And for the large reciprocating compressors, the efficiency can be higher than 80%[65].

Then the consumption for compressing can be derived by the following formula based on the inlet and outlet states:

$$\text{Actual consumption} = \frac{(\text{enthalpy @ outlet pressure same entropy}) - (\text{enthalpy @ inlet temperature and pressure})}{\text{isentropic efficiency}} \quad (3.1)$$

For the low or medium pressure one, the inlet pressure is assumed to be 30bar with 15℃ based on the parameter of electrolyzer, the outlet pressure is 200bar to meet the requirement of the storage tank. The properties of hydrogen at related statements are referred to the engineering software EES[68] (Engineering Equation Solver). Then based on the above equation, the consumption should be 1.3 kWh/kg for now. In the future scenario, since the storage tank increases to 400bar, though the isentropic efficiency is increasing, the consumption will not reduce. It will be 1.7kWh/kg in the future. The detailed calculation process is indicated in Appendix E.

For the high pressure one, the current scenario uses the data from real commercial refueling device produced by Linde. The overall consumption of the high-pressure compressor system is highly based on the inlet pressure. Since the inlet pressure should be various from 50bar to 200bar (or 450bar in the future), the consumption is assumed with the minimum pressure condition, which is 2.7 kWh/kg H_2[63][69]. The future consumption is referred to the report [48]. The same consumption reduction percent (58%) is assumed for the future scenario which makes it be 1.6 kWh/kg H_2. The throughout loss is quite small for now (less than 1%[59]), so the impact of H_2 loss is neglected in the model.

The high-pressure compressor system actually contains many auxiliary devices (just like Linde's product shown in Figure 27), but the main consumption is from the compressor itself. In the model, the 2.7kWh/kg is assumed to be the total energy consumption for the compressing process and used to estimate the cost of the compressor.

The cost of the compressor is based on the HDSAM model (version3.0)[70], according to the compressor cost calculation formula for the low-pressure and high-pressure compressor. (in USD_{2007})

$$\text{Uninstalled Cost} = \$40{,}528 * kW^{\wedge}.4603 \text{ for storage compressor} \quad (3.2)$$

$$\text{Uninstalled Cost} = \$40{,}035 * kW^{\wedge}.6038 \text{ for 700 bar refueling} \quad (3.3)$$

The rated power for compressor here is simply estimated by its rated flow rate and unit energy consumption. The results show the uninstalled capital is \$5500/kg H_2/h for the low-pressure compressor and \$21200/kg H_2/h for high-pressure one. Besides, NREL panel indicates the high-pressure compressor cost is about \$14200/kg H_2/h to \$17900/kg H_2/h[59] after discussing with some vendors, which also assumes that the cost of the medium-pressure compressor is about \$5000/kg H_2/h.

In conclusion, The low-pressure and high-pressure compressor cost is assumed to be €5000/kg H_2/h (HDSAM model result) and €16000/kg H_2/h (average value based on the analysis above), respectively. The future reduction is assumed to be 50% according to the optimized calculation from NREL[59]. The O&M is 4% of the investment for now and 2% in the future also according to the DOE study[65]. Moreover, one replacement is considered for compressor during the 20 years' system lifetime but assume no backup is required in the future as the optimal assumption.[59]

3.3.5 Dispenser

Dispensing is the last procedure for the FCEV refueling. It uses the dispenser to inject the hydrogen from cascade tank to the storage tank in the FCEV. The hydrogen needs to be cooled down to -40℃ for a quick and efficient fueling process[62], so a chiller is also required for the dispenser.

The type of dispenser is defined by both FCEV and the refueling system. According to the same standard (SAE J2601) and the technical parameter from Linde integrating refueling system[63], the dispenser is modelled for 70MPa refueling with flow rate of 60g/s. It draws the hydrogen from 100MPa cascade to fuel the storage tank in the FCEV. Since the hydrogen tank in the FCEV usually can keep around 5kg hydrogen[66], to fuel one car from empty to full only needs less than 2 minutes. For 700bar fueling, the pre-cooling is necessary. In the model, it consumes 0.2kWh/kg H_2 and for now 0.15kWh/kg H_2 and in the future.[48]

The cost is referred to the NREL study, a two-hose dispenser costs \$110500 for each, and the cooling system price is \$133000/ kg/min capacity. An optimal cost reduction as 13% of the price for now is assumed for the mature market in the future scenario.[59] O&M cost is referred to the reference[48]. The lifetime is 10 years for now[48] and no replacement required is required for the future scenario.

3.3 Chapter summary

In this chapter, all the devices composed of the wind-powered refueling system are introduced and the parameters used in the following modelling and simulation are defined at the same time. The overview of the system is shown below.

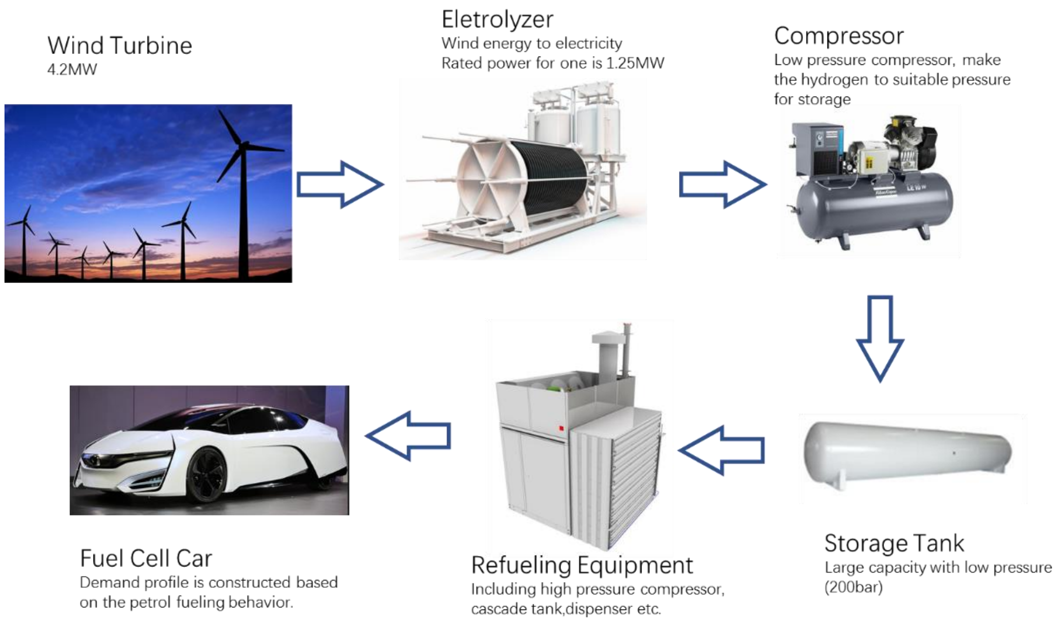


Figure 28 The overview of wind-powered hydrogen refueling system

Also, the parameters used for simulation are listed in Table 6. The detailed dimensioning is defined based on case study. Here only the efficiency or the unit consumption for each process is addressed.

Table 6 The system components summary

Device	**Parameter**	
	Now	**Future**
Wind Turbine [41]	E141-4.2MW Enercon	
Electrolyzer Referred from Proton[55] and Siemens product[12]	Constant overall efficiency 67%	Constant overall efficiency 75%
Tap water consumption[12]	16.67kg/kg H_2	
Low-pressure compressor [59][67]	Isentropic efficiency 65% 1.3kWh/kg (30bar→200bar)	Isentropic efficiency 80% 1.7kWh/kg (30bar→400bar)
Low-Pressure Tank [59][60] (two stationary tanks and one mobile backup tank)	Low-pressure tank (200bar) 400kg capacity for each	Medium-pressure tank (400bar) 400kg capacity for each
High-pressure compressor system [48][63][69]	Overall energy consumption rate:	Overall energy consumption rate:

Referred from Linde product	2.7kWh/kg	1.6 kWh/kg
Cascade Tank[62][63]	100MPa, capacity is based on the demand request	
dispenser pre-cooling system[48]	0.2 kWh/kg H_2	0.15 kWh/kg H_2

The wind turbine only has a future cost reduction but the power curve is the same so that the wind energy production does not change. The other components have an efficiency increase in the future scenario. For the low-pressure compressor, although the isentropic efficiency is increasing, the outlet pressure is also rising, which makes the consumption increase.

Table 7 shows the summary of the cost issues. Since the energy consumption for high-pressure compressor in this model also counts in some other auxiliary equipment, the result should be a little overestimated.

Table 7 Cost summary for all the components*

Device	**Capital [a]**		**O&M [b]**		**Comments**
	Now	Future	Now	Future	
Wind Turbine [4][46][47]	€1100/kW	€800/kW	€60/kW/year	€46/kW/year	Installed capital
Electrolyzer [53][54][56][57][58][48]	€1200/kW	€250/kW	2.5%		Installed capital
Storage tank [48][59][60][64]	€870/kg (low)	€500/kg (medium)	1%		
High-pressure tank (Cascade) [48][59][60][65][66]	€1180/kg	€610/kg	1%		
Low-pressure Compressor [59][65][70]	€6500/ kg H_2/h (low)	€3600/ kg H_2/h (medium)	4%	2.5%	One replacement is required for now
High-pressure Compressor [59][65][70]	€20800/ kg H_2/h	€9600/ kg H_2/h	4%	2.5%	
Dispenser [48][59]	€130000/unit	€104000/unit	1.2%		One replacement is required for now
Pre-cooling for refueling [48][59]	€155000/kg/h (capacity)	€124000/ kg/h (capacity)	2%		One replacement is required for now

*** all the price values are converted to euro with $ 1≈ € 0.9**

a. All the cost values are installed capital with the installation factor 1.3 for now and 1.2 for future[59]**, except wind turbine and electrolyzer which is already including the installing cost.**

b. The percentage values are based on the installed investment

4. Refueling station control strategy design based on the case study

The refueling system model needs to be dimensioned and simulated based on local meteorological condition and demand profile. In this chapter, the system sizing and control strategy will be introduced via a case study. One suitable station after filtering is picked out and the wind-powered hydrogen refueling station will be established and simulated based on the data at this location.

4.1 Demand profile construction

First of all, the demand profile for the refueling station should be defined, which need to be used as the demand input for the simulation. Since there are quite few data from a commercial hydrogen refueling station, this demand profile will be derived based on the investigation of daily consumption for the commercial petrol station.

Chevron plotted the daily and weekly demand profile according to the refueling profiles survey from their 387 company-owned outlets.[71] The hourly distributed profiles in one week are shown in Figure 29 to Figure 31.

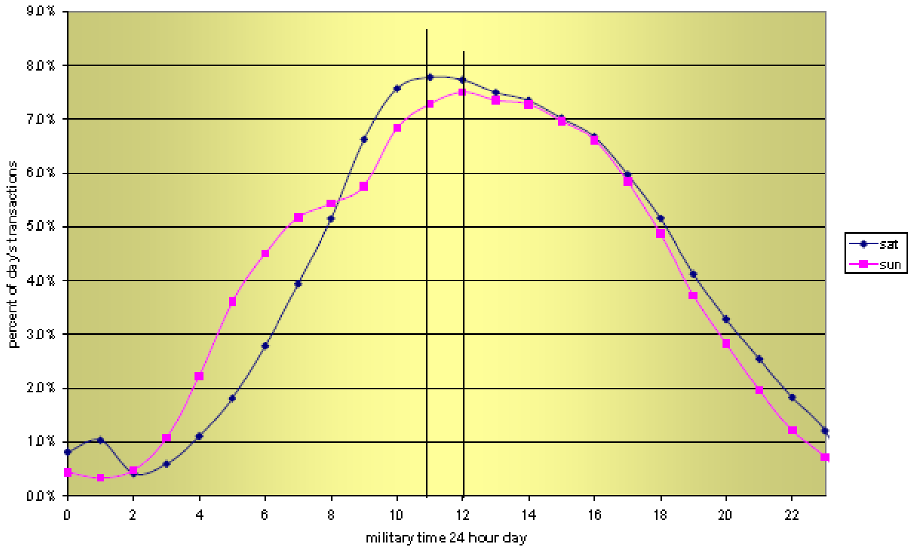


Figure 29 Demand profile for weekends

During the weekends, the peak of demand appears in the noon, which means people usually go out late in the morning for some short distance travelling. But for the weekday, there are two peaks appearing in the morning and evening, which means the refueling often occurs on the way to and work and back home. And the stations serve more in the evening than in the morning.

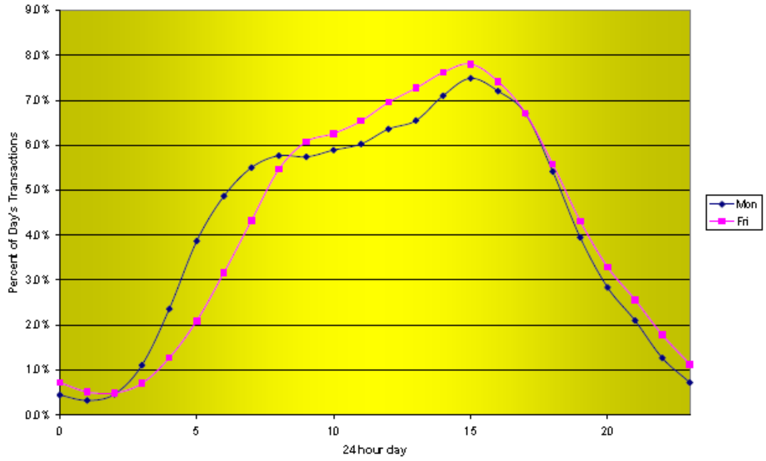


Figure 30 Demand profile for the beginning and end of workday

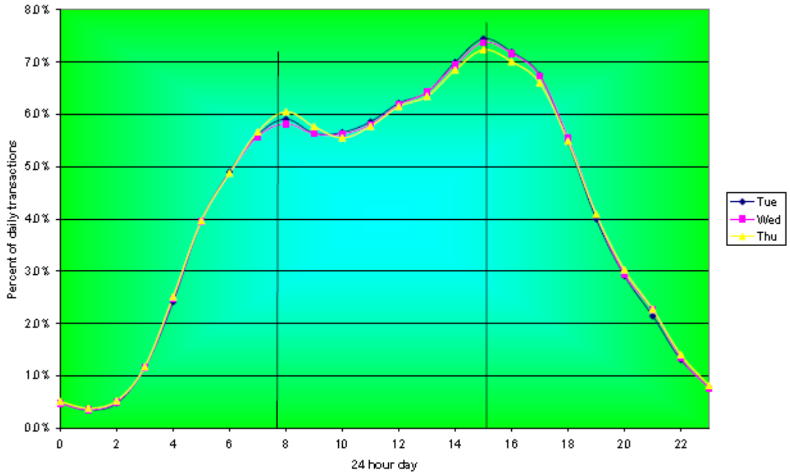


Figure 31 Demand profile for the other workday

According to these distributed profiles, the daily demand pattern can be derived. Reddi et al. construct the hydrogen refueling demand for a 250kg/day shown in Figure 32[67]. The demand profile is assumed to be the same for every day.

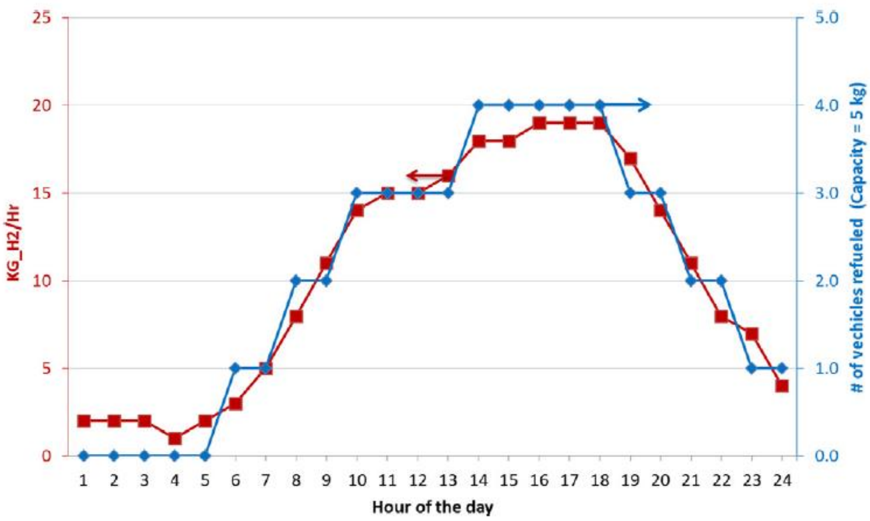


Figure 32 Demand profile for a 250kg/day hydrogen station

To make it a more precise model, the varying daily distribution is used throughout the week while the total demand for every day keeps constant.

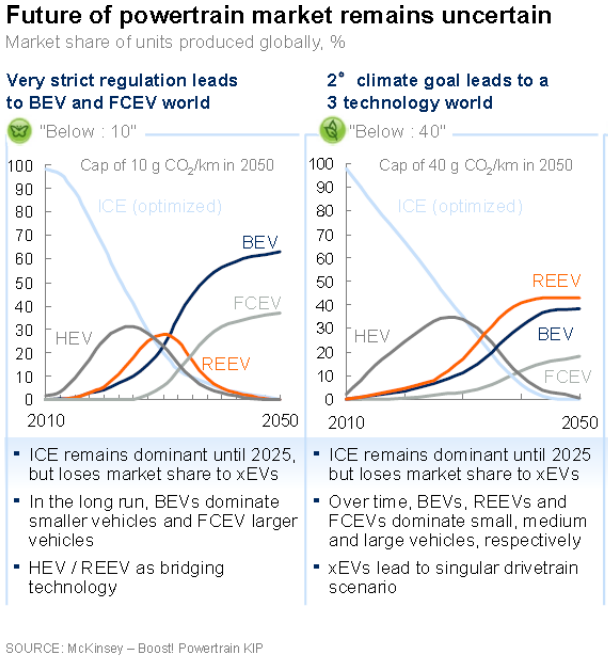


Figure 33 Long-term vehicle market prediction in Europe[72]

Meanwhile, the average daily demand for the hydrogen refueling station is 1000kg/day in Germany according to the study of petrol consumption for transports[73]. For the less carbon-emission mobility future, the whole market is assumed to be occupied by renewable energy vehicles, among which 20%-40% are FCEV based on the roadmap from McKinsey shown in Figure 33. To fulfill the energy demand of fuel cell cars, the scale of hydrogen refueling station is estimated to be 330kg/day.

In conclusion, the demand profile is designed for a 330kg/day refueling station with the daily distribution acquired from the petrol demand of gasoline station. The demand profile for the whole week is illustrated in Figure 34.

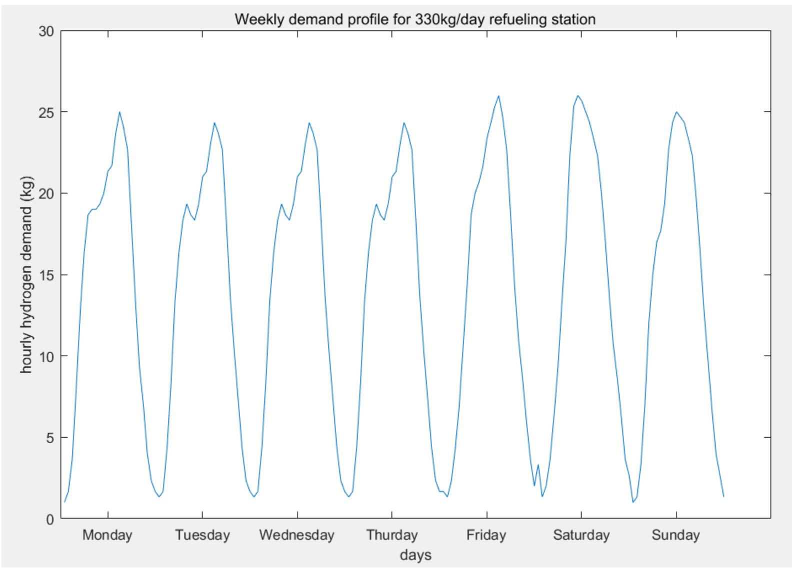


Figure 34 Weekly demand profile for the model simulation

4.2 Location choice and system scale definition

4.2.1 The local geographical and meteorological condition

The key criteria are whether the hydrogen production is enough to cover the demand and whether such system is the feasible solution for hydrogen refueling. These problems are mainly determined by the wind energy quality at the station. There are 525 stations left after applying the selecting method in Chapter 2. Since most part of Germany drops in Class III and Class IV wind speed area and most of the stations are located near the motorway or primary route according to the alternative filter in Chapter 2.2.5, the case in Class IV and near the motorway or primary route will be representative.

Therefore, the station located at the coordinate (50.0574N, 8.449E) is chosen from previous-mentioned qualified candidates. Figure 35 is the regional map of the station in Google map. It is located beside the motorway and around it is the arable land.

Figure 35 The location condition of the selected petrol station

Then the climate data at this location is obtained from the nearest meteorological station. Although this climate observer is 5km away from the petrol station (coordinate of the weather station is 50.0259N, 8.5213E), it provides the most accurate data available. Actually, the in-situ wind condition needs to be measured before wind turbine installation by setting the instrument near the station.

In the simulation, the applied wind speed data are derived from the Climate Data Center of Deutscher Wetterdienst[74], which are converted into hub-height speed first via the method in Appendix B before simulation.

4.2.2 System dimensioning based on the case study

For a 330kg/day station, its annual hydrogen consumption is 120 tons. Considering the electrolyzer efficiency, the annual energy consumption should be about 4700MWh. Meanwhile, the annual wind production for single 4.2MW wind turbine is approximate 12000MWh according to the local wind data. Thus, only one wind turbine is enough to serve the refueling station and the wind energy balance and management should be the major issue for the whole system.

The other system components dimensioning will be all based on the wind turbine scale. To utilize the wind turbine efficiently, the electrolyzer is chosen as 3.75MW (right three Siemens products), which means the rated capacities of electrolyzer and wind turbine match with each other approximately. Thus, the flow rate is 70kg/h for the low-pressure compressor, which matches the production capacity of the electrolyzer.

The scale for refueling part is defined by the demand. From the demand construction part, the peak demand is around 26kg/h, which means 5 cars are fueled at most in the same hour. The cascade capacity should be designed to cover the peak demand so the high-pressure hydrogen is assumed to be 30kg. The operational pressure for high-pressure storage tank (cascade) is assumed from 700bar to 1000bar. If the available hydrogen capacity is 30kg, the actual cascade capacity should be larger than this value. Here the capacity is roughly estimated by ideal gas law:

$$PV = nRT \tag{4.1}$$

For a given cascade capacity, the volume is constant, if the temperature is also assumed to be constant, then the n (the quantity of matter) will be linear with P (pressure). Thus, the capacity should be around 100kg for the cascade so that it can release 30kg hydrogen from 100MPa to 70MPa.

Since it only takes several minutes for refueling. The station designed to serve 4 cars at the same time is fairly enough, which means two dispensers with two hoses for each are enough and the cooling system is also sizing based on maximum dispensing flow rate. The flow rate for the high-pressure compressor is derived from Linde's ionic refueling device[63]. The following table gives the summary for the scale of the system components

Table 8 The scale of system for case study

Device	Parameter
Wind Turbine	E141-4.2MW Enercon
Electrolyzer	3.75MW (Referred from Siemens) Rated output is about 65kg/h
Low-pressure compressor	Flow rate 70kg/h
Low-Pressure Tank	Low-Medium pressure (200bar for now and 400bar in the future). 400kg capacity for each, two stationary tanks in total.
High-pressure compressor	Flow rate 33.6kg/h (Referred from Linde product)
Cascade Tank	Capacity 100kg
Dispenser (two)	3.6kg/min for each (Referred from Linde product)
Pre-cooling system	Flow rate 7.2kg/min

4.3 Control strategy development

The good control strategy is very important for the system. Since the wind energy is uncontrollable, how to use it efficiently would be the key purpose for the system. This section will show the development of system control logic. Two targets are achieved: Maximizing the wind energy utilization and minimizing the capacity for grid connection. In addition, the basic principle and performance of control strategy are introduced. The detailed flowchart and explanation can be found in Appendix F

4.3.1 Primary control strategy

The basic control logic will be introduced in this part. Figure 36 shows the schematic of all the components of the system.

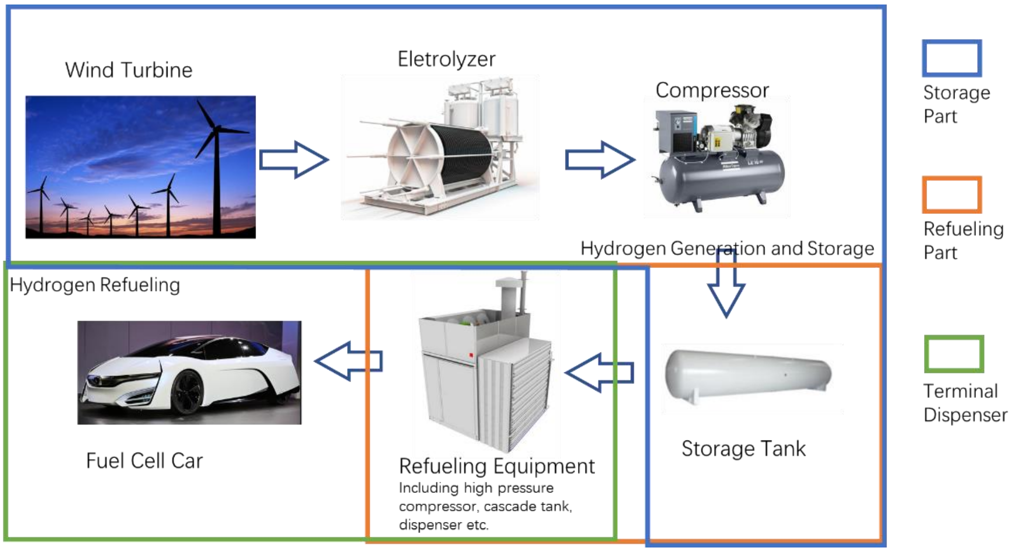


Figure 36 The schematic of the system

The system is divided into three parts, the storage, refueling and dispenser parts. These three parts are controlled individually. The intersection for storage and refueling parts is two low-pressure tanks and for refueling and dispenser parts is the cascade tank.

For the storage part, the control target is to produce hydrogen as much as possible and ensure enough space for hydrogen storage. Since the rated capacity of electrolyzer and wind turbine is not same, first checking if the wind energy in a certain hour exceeds the electrolyzer capacity or not. If the excess part is high enough, it will be used for compressor demand or injected into the grid if all the demand has been covered.

As depicted in Figure 37, the hydrogen is compressed by the low-pressure compressor first, which needs to consume electricity from either excess wind energy or grid energy. Then, they are stored in the connected tank (named as storage tank). When the current storage tank is full, it will be replaced with another low-pressure tank connected with the refueling part (named as refueling tank). The full storage tank becomes the new refueling tank (i.e. switching these two tanks). This can be realized by two three-way valves, one is located at the outlet of the electrolyzer to choose which tank will be filled (to be the storage tank) and the other one is located at the downstream of two tanks to determine which tank is responsible for delivering the hydrogen to the refueling part. These two tanks are regarded as the stationary storage devices.

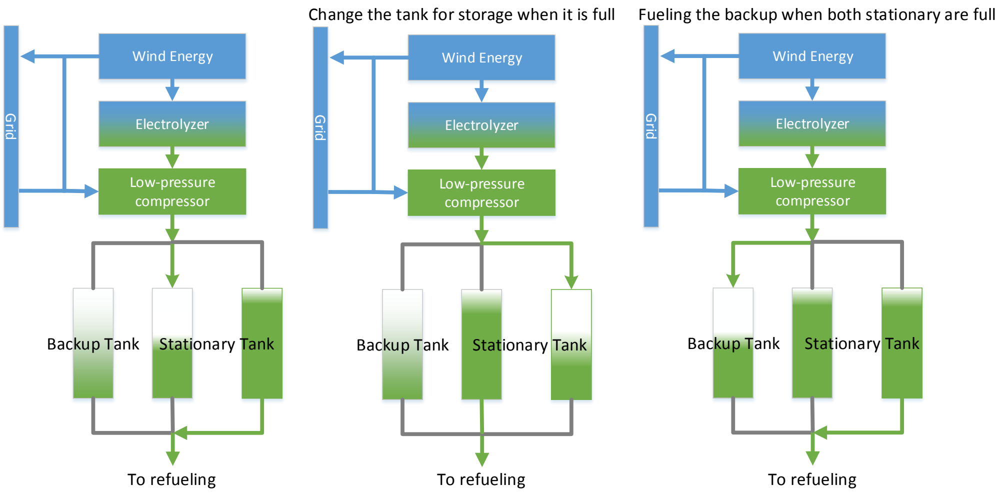


Figure 37 Control logic for storage part

In addition, there is another low-pressure tank called backup tank. It is used to store the hydrogen if the other two tanks are both full. This backup tank is assumed to be demountable which means it can be disassembled when it is full and replaced by another empty one. In practice, this tank will be designed to fit the truck or trailer in order to be transported and sold to the other hydrogen retailer via the road network and bring the empty tank back to the station. This mobile backup tank enables the infinite backup capacity so that there is no storage capacity limitation for hydrogen. The mobile tank can be replaced by an empty tank whenever it is full. Another idea could be that a hydrogen pipeline network is already installed and the system can deliver the hydrogen to the nearby communities. This idea will also be discussed later in the Recommendation part.

The second part is the refueling section presented in Figure 38, this part is to keep enough hydrogen in cascade for refueling vehicles. First a state level for cascade is set as 25kg, which is based on the maximum demand in one hour. If the cascade state is lower than this value, the refueling system will draw hydrogen from the low-pressure tank and fill the cascade until it is full.

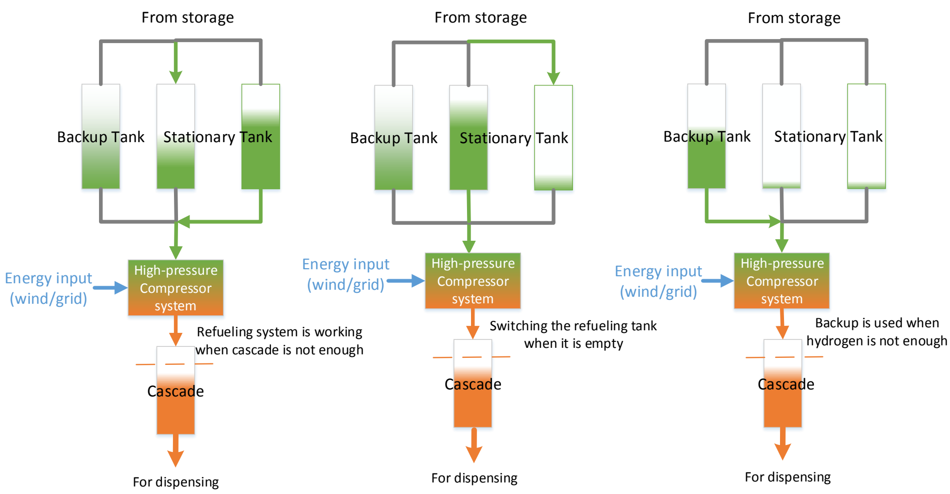


Figure 38 Control strategy for refueling part

During this process, the state of low-pressure tanks also needs to be checked. Similarly, if the current refueling tank is not enough, it will be exchanged with the other low-pressure tank (storage tank). The backup tank is used when both of two tanks are empty. Such control strategy is also achieved by using two three-way valves.

The last part is the terminal dispenser. After the refueling part, the cascade always has enough hydrogen for fueling, so the control logic for this part is very simple. The system draws hydrogen from cascade and delivers it to the pressure tank in the cars. Based on the refueling model in Chapter 3, Extra energy from grid will be consumed for the pre-cooling before dispensing.

The climate data for 2016 is the input for the simulation, the behavior of hydrogen production is shown in Figure 39. It shows the wind energy is more abundant in winter and spring than that in summer because the lines for high production (>40kg/h) are denser in winter.

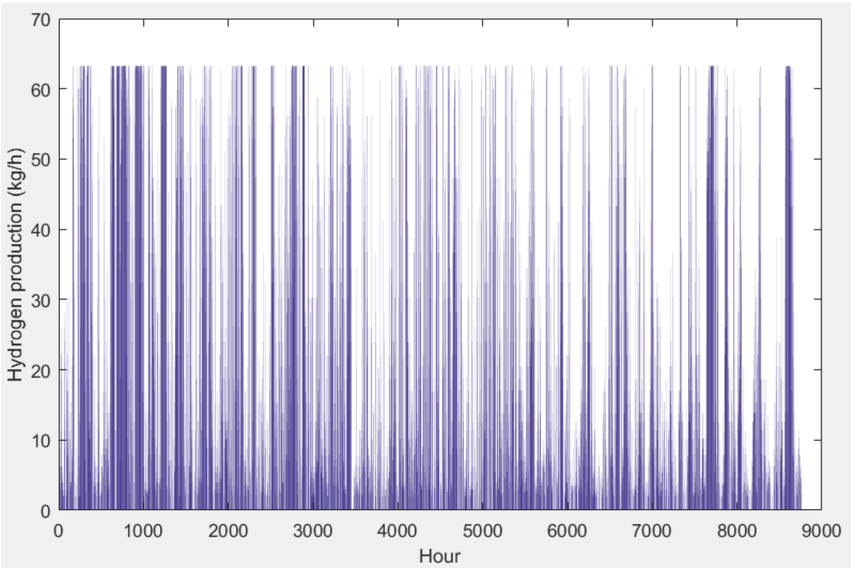


Figure 39 Profile for hydrogen production

It is clear that when both the electrolyzer and wind turbine operate under their rated capacity, there appears energy mismatch. As a result, some energy will be excess. In the control strategy above, this part of energy will be injected into the grid if it is too small to use.

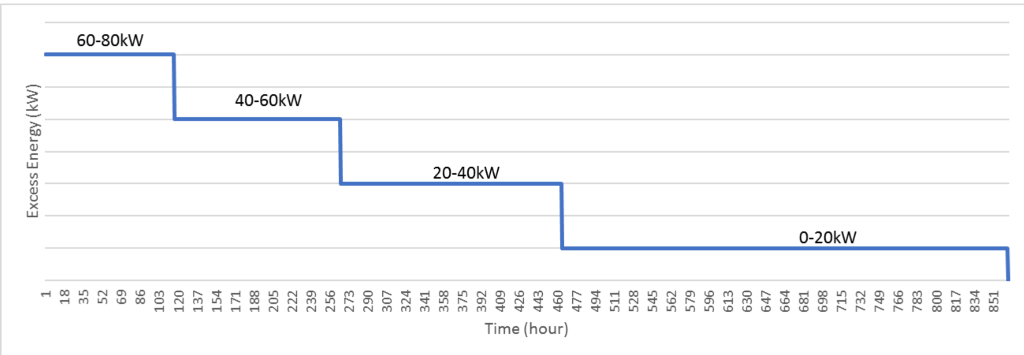


Figure 40 The excess energy duration curve throughout one year (8760 hours)

Although the excess energy in one hour is little shown in Figure 40, which only appears in 860 hours, the accumulation for one year can be even a large amount of energy about 24.6MWh, which can be used in a more efficient way.

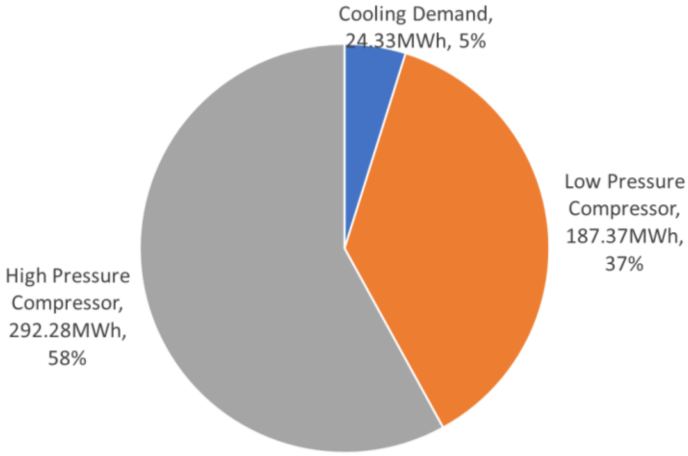


Figure 41 Annual grid consumption distribution

Another problem is that the system needs a very large grid capacity. It requires about 500MWh energy from the grid with a peak of 155.7kW annually. This consumption comes from the electricity load of compressors and cooling system shown in Figure 41. Since the energy produced by the wind turbine is much higher than the hydrogen production consumption of the electrolyzer, it is unnecessary to introduce a very large grid capacity which would increase the investment of system.

In this case, an improved control strategy is raised to solve these problems.

4.3.2 Pre-allocation

The reason for wind energy excess is that the system produces as much as hydrogen first, which makes only very small piece of wind energy left. Under this circumstance, the compressor would prefer total grid power rather than using this tiny wind energy combining with the grid electricity. The compressors always need a stable power supply since the rotation devices require power resource with stable input and frequency.

Meanwhile, according to the operating mode of the system, it is easy to derive that the electrolyzer and low-pressure compressor are coupling all the time, which means they are always working at the same time. (Once the hydrogen is produced, it needs to be compressed and stored.) However, the refueling system is independent of these two devices. It functions only when the cascade is not enough, and the cascade state is only affected by the demand. Another fact is that the refueling system would consume much more energy than the low-pressure compressor and pre-cooling device according to the current scenario in Table 6.

Therefore, the improved control strategy will not emphasize the maximum hydrogen production but focus on wind energy usage. The wind energy is consumed for high-pressure compressor system first, the rest energy is pre-allocated so as to rightly cover the total energy consumption for both electrolyzer and low-pressure compressor. The flowchart of wind energy is shown in Figure 42. Similarly, if the wind energy is not enough to cover the demand of high-pressure compressor system, the electricity from the grid will be introduced to compensate the lacking part, but the low-pressure compressor can be stand-alone with the grid, which means the grid connection for it in Figure 37 is eliminated.

The electricity requirement for pre-cooling system appears in every hour with very small quantity, so a constant and continuous energy supply by the grid may be preferred.

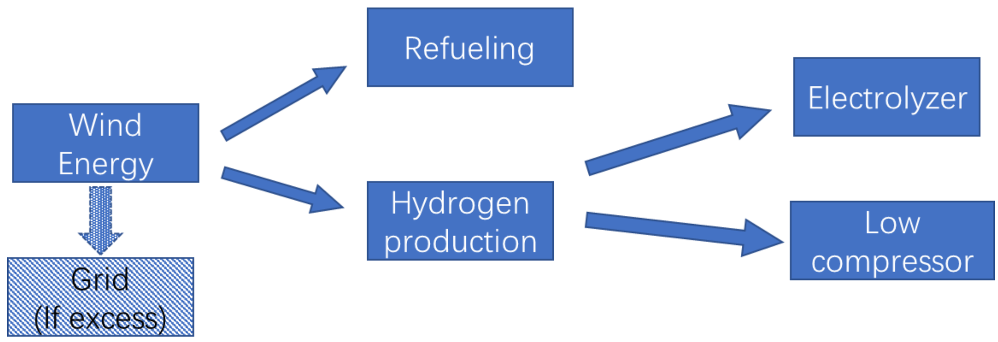


Figure 42 Wind energy flowchart for a pre-allocation method

In this control strategy, one of the significant differences is that the low-pressure compressor becomes totally off-grid since all of the energy requirement will be covered by pre-allocated wind energy. Although the hydrogen production is reduced a little bit (because more wind energy will be used for compressing process), the excess wind energy can be utilized in a better way as well as reducing the grid consumption.

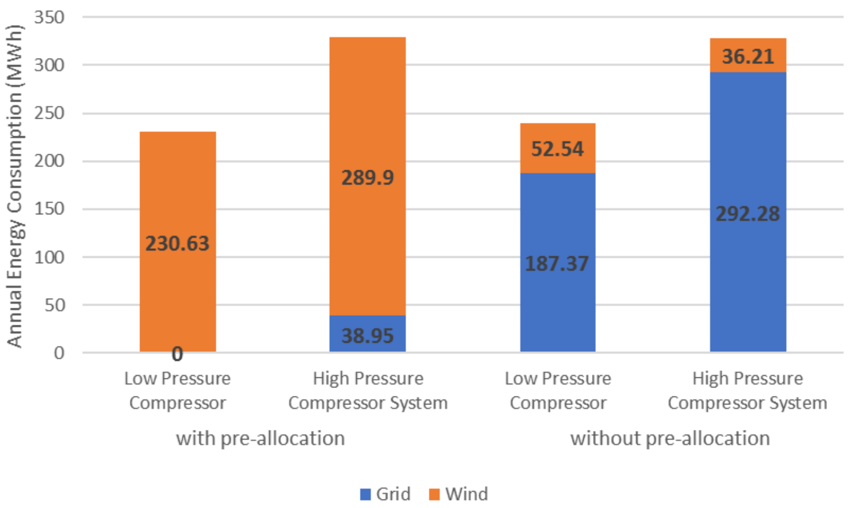


Figure 43 The energy resource share for compressor demand

Figure 43 shows the energy share for compressing and refueling consumption with and without the pre-allocation strategy. The pre-allocation can make more wind energy involved in the system operation. It will reduce both the grid electricity consumption and the excess wind energy that would be injected to the grid.

4.4 Simulation result analysis

The simulation results for both current and future scenario are discussed in this section. Moreover, the simulations based on the climate data from different years are performed to show some general system feature.

4.4.1 Comparison for current and future scenario

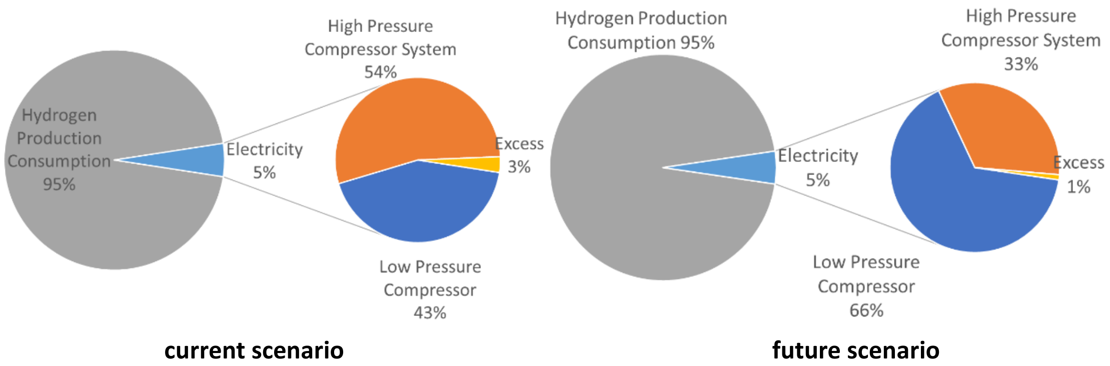


Figure 44 Wind energy utilization distribution for pre-allocation strategy

Figure 44 depicts the energy utilization with a pre-allocation control strategy, the excess electricity is very small, which means nearly 100% of wind energy is consumed by the system. Nearly 95% of wind energy can be used for hydrogen production in both cases. The only difference is that the high-pressure compressor system consumes less in the future because of the more efficient compressing process. Since more hydrogen will be produced and the stationary tank will be upgraded to 400bar in the future, the low-pressure compressor consumption will increase to achieve this.

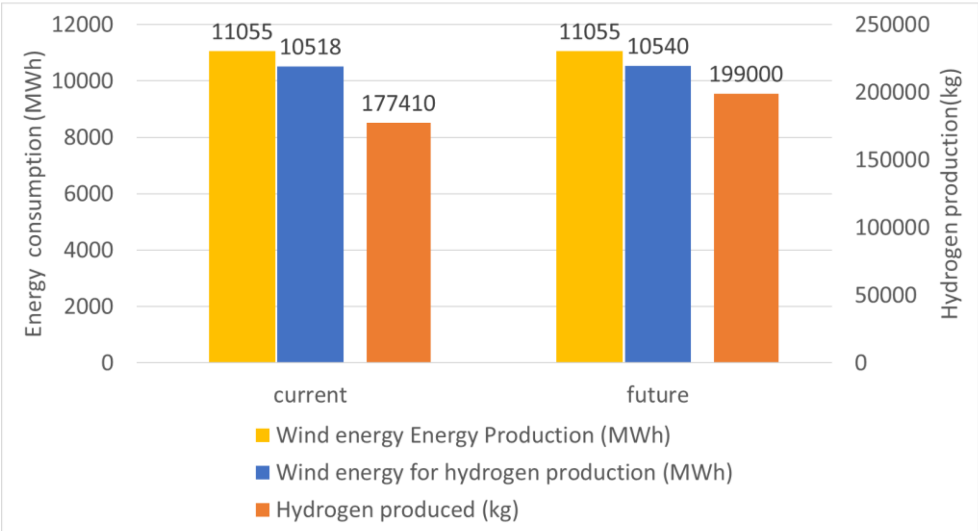


Figure 45 Annual wind and hydrogen production for different scenarios

Figure 45 shows the comparison between the two scenarios. The wind energy production is the same because of the same wind turbine and climate data input. The future scenario would give more energy to hydrogen production process thanks to the efficiency increase of CSD system (i.e. low energy consumption for per kilogram hydrogen). Another fact indicated on the plot is that the hydrogen yield will increase by over 10% in the future because of the high conversion efficiency of the PEM electrolyzer.

Meanwhile, according to the annual wind energy production, the capacity factor of the wind turbine can be calculated as:

$$cf\% = \frac{Annual\ energy\ yield\ (MWh)}{Hours\ in\ one\ year*Power\ capacity\ of\ wind\ turbine} = \frac{11055MWh}{8760h*4.2MW} = 30\% \qquad (4.2)$$

The capacity factor is about 30% at the location chosen for the case study. Since the station for the case study is located in the Class IV wind speed area, the capacity factor would increase if the wind-powered refueling station is established in the high wind speed area.

Similarly, the utilization factor is defined for the electrolyzer:

$$uf\% = \frac{Annual\ energy\ consumed\ by\ electrolyzer\ (MWh)}{Hours\ in\ one\ year*Power\ capacity\ of\ electrolyzer} = \frac{10518MWh}{8760h*3.75MW} = 32.0\% \qquad (4.3)$$

The utilization factor will increase to 32.1% in the future since the energy consumption for electrolyzer increases a bit. The low utilization factor indicates that the electrolyzer is not used very efficiently, which means it may be oversized in the model.

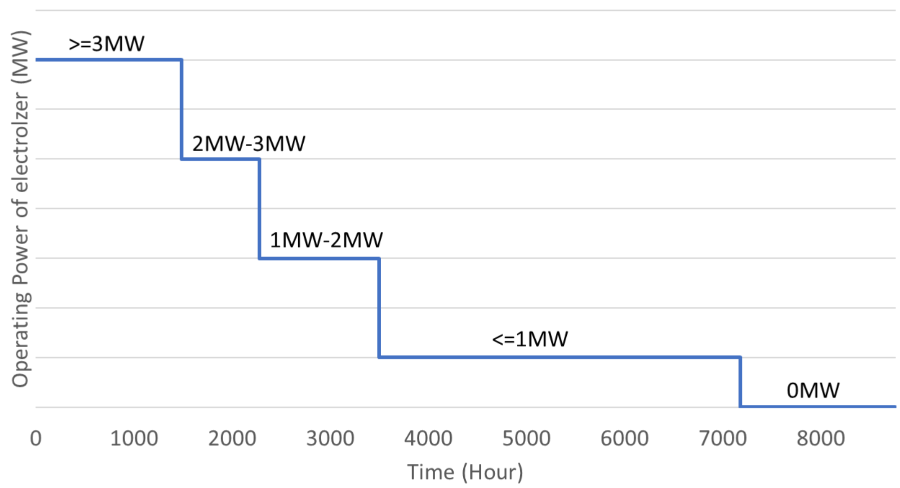
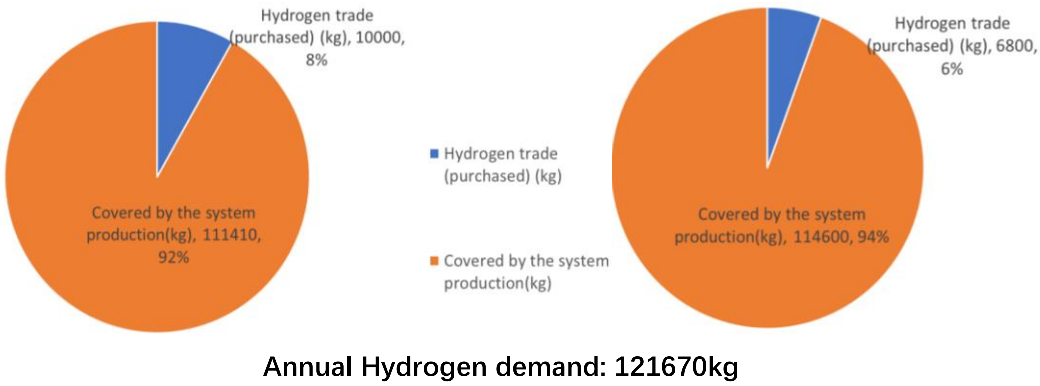


Figure 46 Energy consumption duration curve for electrolyzer

The similar result can be concluded also from the electrolyzer energy consumption duration curve shown in Figure 46. Although the electrolyzer is dimensioned based on the wind turbine capacity, the low capacity factor makes the energy delivered to the electrolyzer is much lower than its rated capacity for most of the time. The electrolyzer can consume over 3MWh energy only in 15% of one year. In most of the time, the energy consumption for electrolyzer is around 1MWh. There are even about 12% of the time when the electrolyzer does not operate because wind energy production is not enough. Therefore, the electrolyzer capacity can be downsized in the future research or dimensioned based on the actual wind energy production at the station, which will reduce the investment of the whole system.

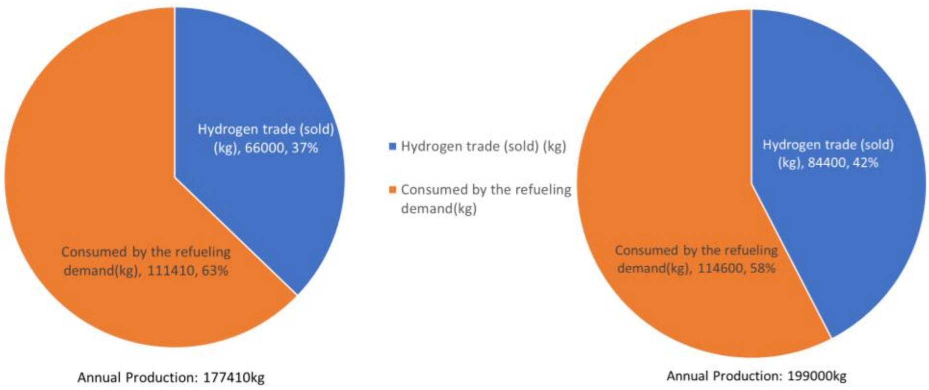
Furthermore, the pattern of hydrogen production and utilization is illustrated in the Figure 47.



current **future**

Figure 47 The hydrogen source for demand covering

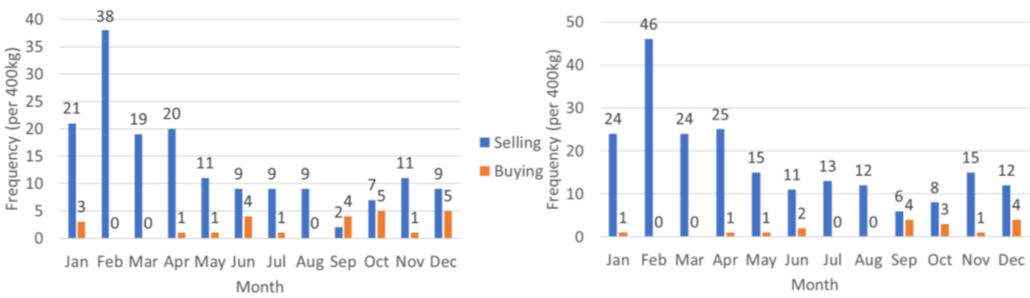
Figure 47 indicates that over 90% of the hydrogen demand can be covered by on-site water electrolysis production while 7% of demand needs the external supplier. This external supply only happens when the on-site storage is used up, which means the wind energy is too little to produce enough hydrogen for several days.



current **future**

Figure 48 The hydrogen production whereabouts

Since the production is more than the demand, the excess hydrogen production can also be sold via the hydrogen transport network. There are about 40% of hydrogen sold to the other retailers or industrial companies, which is also part of the income of station. In the future, more hydrogen is sold because the demand does not change while more hydrogen is produced.



current **future**

Figure 49 Hydrogen transport frequency summary

As shown in 3.3.3, the hydrogen transport or distribution can be done by the tube/container trailer.

Figure 49 indicates the frequency that the trailer needs to visit per month if every time only one tank can be delivered (400kg per visit). There is more hydrogen production in first four months. As a result, the trailer nearly visits the station every day to collect the full tank.

However, the maximum transport quantity can be customized based on the request, which can reach over 1000kg for every visit[61][75][76]. The trailer may visit the station in a regular period to collect more than 400kg hydrogen for sale or deliver the backup hydrogen if necessary. In the future, it can also be done by the pipeline with even low cost if the market gets mature.

This system still needs to be connected to the grid to ensure continuous operation in case that the wind energy is not enough and power the dispenser cooling system. Dispensing cooling system consumes 0.2kWh/kg H_2, so it should be about 60kWh per day, which is quite small.

After applying the pre-allocation control strategy, the grid consumption for the low-pressure compressor is eliminated and only very small part is required for high-pressure compressor system.

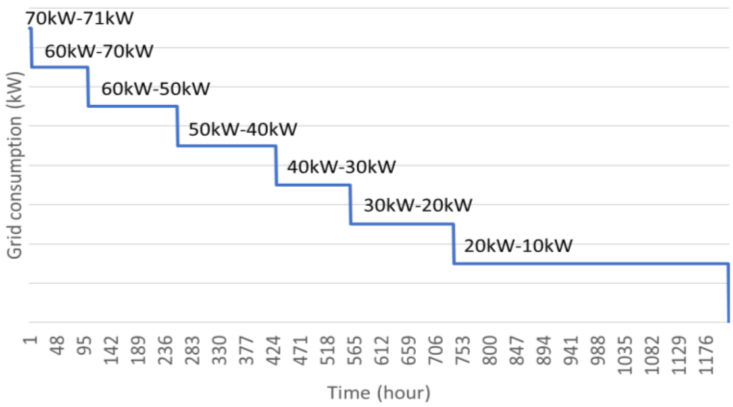


Figure 50 Grid consumption duration curve of high-pressure compressor system for one year (8760h)

Figure 50 shows the grid demand duration curve of the high-pressure compressor system. The maximum power requirement is about 70kW, and for most of time it is either zero or less than 20kW. Actually, throughout one year (in 2016 for example), no grid energy request from the high-pressure compressor in over 7000 hours. That is to say, the period of grid energy supply for the high-pressure compressor is just 13% of the year.

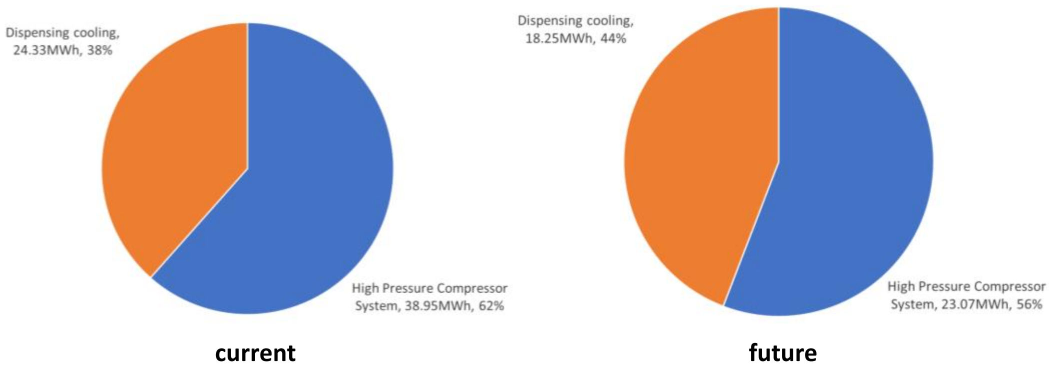


Figure 51 The grid consumption distribution

The total grid consumption for these two parts is shown in Figure 51. The annual consumption from the grid is about 63 MWh, which is only 0.5% of the wind energy consumption of the system. The grid requirement is quite little so that no grid capacity upgrading is necessary.

4.4.2 Climate data sensitivity

Furthermore, the study demonstrates the impact of climate condition variation. The climate data for 2015 at the same location is also used in the current scenario model.

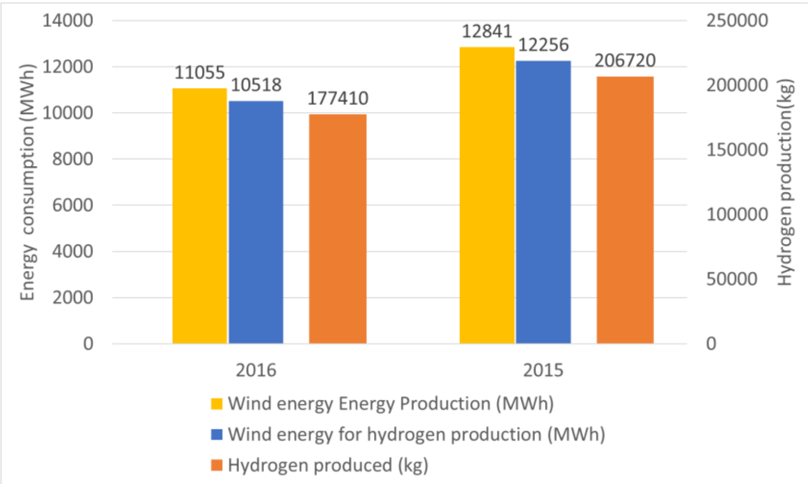


Figure 52 Annual wind and hydrogen production of different years

The wind energy production is about 15% higher in 2015 than that in 2016 shown in Figure 52, so more hydrogen is produced in 2015. It also leads to high low-pressure compressor consumption in 2015 because of hydrogen compressing and storing process. However, the consumption for high-pressure compressor system does not change since the demand is the same, which makes the low-pressure consumption share increase to 45% in Figure 53.

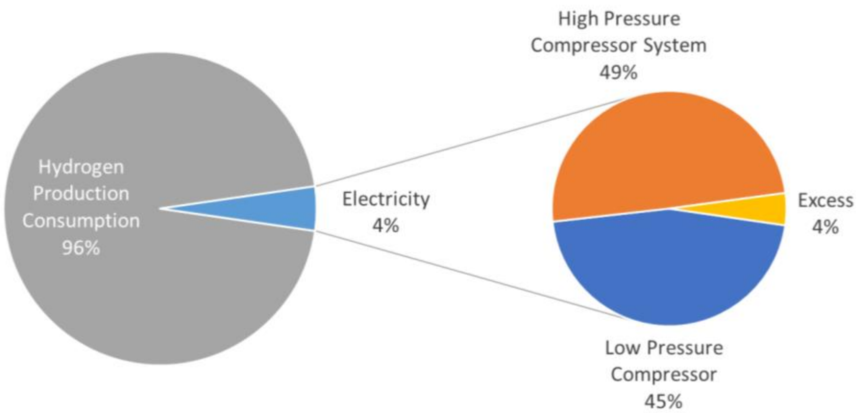


Figure 53 Wind energy utilization distribution for current scenario with 2015 data

Meanwhile, the wind energy utilization distribution of 2015 current scenarios does not change too much comparing with Figure 44. There is also around 95% of wind energy used for hydrogen producing. The rest of the wind energy is consumed by the CSD system demand as the electricity. It indicates that the system has a stable operation throughout different years.

4.5 Chapter summary

In this Chapter, the hydrogen refueling system with on-site electrolyzer powered by wind energy is designed and simulated. The main parts of the system include wind turbine, electrolyzer, compressor, storage tank and dispenser. Each part has been discussed both in technical and economic aspects. Then it is simulated based on the case study on one specific petrol station in Germany. To minimize the grid capacity requirement and increase the wind energy utilization, the pre-allocation control strategy is developed, which aims to maximize the wind energy using efficiency instead of producing as much hydrogen as possible. With such control strategy, the grid capacity does not need to be reinforcement. The electrolyzer and low-pressure compressor (for storage) can be completely stand-alone with the grid.

After the control strategy development, two cases for the current and future scenario are simulated. Because of the electrolyzer efficiency development, the hydrogen yield will increase about 10% in the future with the same wind energy production. The consumption of high-pressure compressor system also decreases because of high isentropic efficiency in the future. However, the consumption for low-pressure compressor increases about 40% due to the storage pressure upgrading (200→400bar) and more hydrogen production. However, the utilization factor of the electrolyzer is only about 32% in both scenarios because of the low wind energy production at the case study location. It means that the electrolyzer has the potential to be downsized so that the system investment can be further reduced.

For the hydrogen production, about 60% of them can be used for vehicles refueling directly while the other 40% need to be sold. From the demand point of view, about 93% of demand can be covered by the on-site hydrogen production while the rest 7% need to be covered by the external supplier. This is because the wind energy is uncontrollable so that there will be mismatch between the demand and production profile. A better way should be building the hydrogen pipeline network so that the hydrogen can be delivered for the other utility without using trailer frequently.

Finally, the operational stability is checked by using the data from different years. The system shows the similar behaviors by using the 2016 data and 2015 data as the input. although the wind energy is slightly higher in 2015, the wind energy consumption still occupies about 95% of whole wind energy production. The energy consumption for CSD system also shows very similar distribution.

5. System cost analysis

In this Chapter, a brief economic analysis is performed to show the financial feasibility of the system based on the simulation result for both current and future condition. The investment and O&M cost are estimated by the cost for main parts in the system (wind turbine, electrolyzer, compressor, storage tank, dispenser, cooling system). The other cost is roughly summarized as the additional cost that is 23% of the total installed cost including the site preparation, engineering and design, contingency and permitting, according to the interview of the current hydrogen station construction from NREL[59]. However, the system in this report is modified based on the existing petrol station, which means the cost of site preparation and permission should be less. The engineering and design cost would be also reduced in the future. Therefore, 19% and 15% are used for current and future scenarios, respectively.

The economic analysis is based on the levelized cost of hydrogen production (LCOHP), levelized cost of hydrogen dispensing (LCOHD) and the real dispensed hydrogen cost of (RDHC) the system, which will be calculated by the following formula. (Derived based on Levelized cost of electricity (LCOE) equation):

$$LCOHP = \frac{\frac{Wind\ and\ electrolyzer\ parts\ CAPEX}{Annuity\ Factor} + Annual\ wind\ and\ electrolyzer\ OPEX}{Annual\ Hydrogen\ Production} \tag{5.1}$$

$$LCOHD = \frac{\frac{Total\ CAPEX\ for\ CSD\ system}{Annuity\ Factor} + Annual\ OPEX\ for\ CSD\ system}{Annually\ Dispensed\ Hydrogen} \tag{5.2}$$

$$RDHC = LCOHP + LCOHD \tag{5.3}$$

$$\begin{aligned} Annually\ Dispensed\ Hydrogen &= Annual\ Hydrogen\ Demand \\ &\cong Annual\ Hydrogen\ Production - Hydrogen\ for\ sale \\ &+ Hydrogen\ bouhgt\ from\ the\ other\ producer \end{aligned} \tag{5.4}$$

The Annually Dispensed Hydrogen is less than the system hydrogen production, because the system would have hydrogen trade with external communities. The trade will cause extra revenue for the system, which can be estimated by the following equation:

$$\begin{aligned} Cash\ Flow &= (\text{Selling Price} * \text{Hydrogen For Sale}) \\ &- (\text{Purchase Price} * \text{Hydrogen For Purchase}) \end{aligned} \tag{5.5}$$

However, the cash flow will not be taken into account to calculate the Levelized cost quantities for hydrogen production and dispensing in this study because the price of hydrogen trade is highly dependent on the external supplier or the hydrogen buyer. This study would not specify how to define this price.

At the same time, the annual capital cost (ACC) is defined for every component after considering the annuity factor:

$$ACC = \frac{CAPEX}{Annuity\ Factor} \tag{5.6}$$

All the CapEx and OpEx have been introduced in the previous parts. The annuity factor is used to calculate present values of annuities, and equated instalments:

$$AF = \frac{1-(1+r)^{-n}}{r} \quad (5.7)$$

Where n is the lifetime of system (20 years) and r is the discount factor. Here, r is equal to the Weighted Average Cost of Capital (WACC) to get a business's net present value[77]. The current WACC in Germany for renewable energy investment can be as low as 3.5%-4.5% based on the report from Ecofys etc.[78][79].

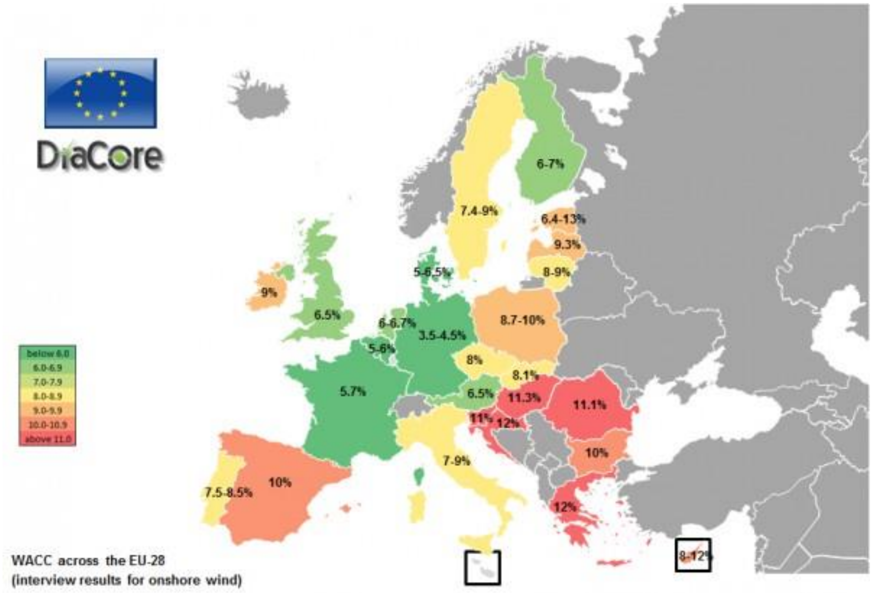


Figure 54 WACC for renewable investment in Europe

Since this is the wind-powered system, WACC is assumed to be 3.5% for now and would reduce to 3% based on the future assumption[48]. Thus, the annuity factor for now and future are 14.21 and 14.9, respectively.

Meanwhile, the refueling station needs to draw a small amount of energy from the grid. The electricity from the grid is referred to the industrial electricity price in Germany, which is about €145-€155/MWh in 2016[80][81]. Here €160/MWh is applied as a pessimistic assumption. The price of electricity sold to the grid is referred to the electricity spot price in Germany, which is assumed to be €40/MWh based on latest survey.[82] Since the grid capacity requirement has been reduced lower than 100kW, the existing grid construction in the petrol station is considered to already meet the requirement of hydrogen refueling station after modification. A brief introduction about the grid investment is still presented in Appendix G based on the related research for the Netherlands and Germany to show the impact of grid connection cost.

5.1 Investment estimation based on the case study

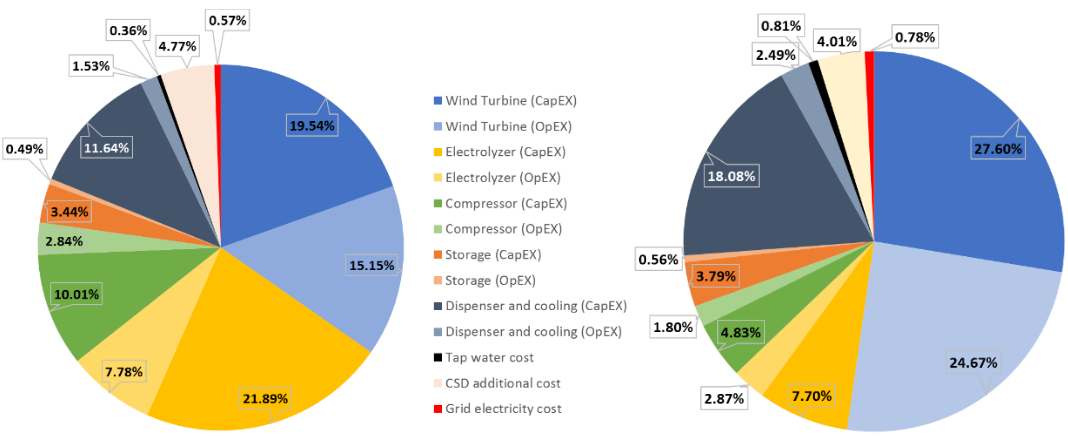
Table 6 in Chapter 3 gives all the basic assumption for the system, and associated with Table 7 and Table 8, the installed capital and O&M cost for a 330kg/day refueling station are calculated and presented in Table 9.

Table 9 The installed investment for the system

	Current		Future	
	ACC €/year	O&M €/year	ACC €/year	O&M €/year
Wind Turbine	325100	252000	225500	201600
Electrolyzer	364200	129400	62900	23400
Compressors (low+high)	166500	47300	39500	14700
Storage*	57300	8100	30900	4600
Dispenser and cooling	193700	25400	147800	20400
Tap water cost	-	5900	-	6600
Grid electricity cost	-	9500	-	6400
Additional cost for CSD installation	79300	-	32700	-
System Capital	1186100	468200	539300	271300
Total Capital	1660000		820000	

*** The investment for low-pressure tanks only includes the stationary one. The backup tank cost will be concerned as part of distribute cost, which is included in the selling/buying cost.**

Table 9 shows the cost summary (installed capital and O&M cost) after being corrected by the annuity factor for both current and future scenarios according to the case study results in Chapter 4. With the R&D progress and more mature commercial market, all of the components have a cost reduction in the future, which nearly half the cost of the whole system. Electrolyzer and compressor would be the fastest developed area. The cost of the dispenser and cooling system should reduce more if more hydrogen refueling station would be built in the future although there are only a few studies focus on their developing pattern.



Current(€1660000/year) **Future(€820000/year)**

Figure 55 Annual capital breakdown for the whole system

Figure 55 is the breakdown illustration of system annual investment (CapEx+OpEx). Wind turbine and electrolyzer are the costly devices in the system. It is true that distributed wind turbine and water electrolysis are both very expensive technologies for now. In the future, with the R&D progress and the increase of volume production for these units when the niche market is established, the cost will be reduced to a large extent for the system, especially for electrolyzer and compressor. The future investment would reduce by 50% because the study gives a very optimistic reduction prediction for electrolyzer and compressors. The cost of tap water and grid electricity are also included since it can be treated as the operational cost, although their cost share is less than 1%.

The other components, storage tank, dispenser and cooling, CSD additional cost and their operating cost contribute about 20% of the system cost in both current and future scenarios. If the cost is divided into production part and CSD part, the cost shares for these two parts are about 70% and 30%, respectively. This result is similar with the analysis made by Air Production[83]. In their research, the hydrogen production and CSD processes share about 60% and 40% of total cost for a grid-powered distributed electrolyzer hydrogen production and refueling system.

5.2 Levelized cost study

The prices of hydrogen produced and dispensed by the system are discussed in this section. According to the related formula, Table 10 shows the calculation results of LCOHP, LCOHD and RDHC values for both current and future scenarios.

Table 10 Summary of cost analysis

	Current	Future
Annual hydrogen production (kg)	177400	199000
Total annual CapEx for wind turbine and electrolyzer (€)	689300	288400
Annual O&M for wind turbine and electrolyzer (€)	381400	225000
Annual tap water cost (€)	5900	6600
Total annual OpEx for hydrogen production (€)	387300	231700
LCOHP (€/kg)	**6.1**	**2.6**
Total annual CapEx for CSD system (€)	496800	250900
Annual O&M for CSD system (€)	80900	39700
Annual grid electricity cost (€)	9500	6400
Total annual OpEx for CSD system (€)	90400	46100
Total annual investment for the CSD system (€)	587100	297000
Annual dispensed hydrogen demand (kg)	121700	121700
LCOHD (€/kg)	**4.8**	**2.4**
Cost price for real dispensed hydrogen (RDHC) (€/kg)	**10.9**	**5.1**

The breakdown plot is shown in the figure below, which divides the cost into production and CSD system (for dispensing).

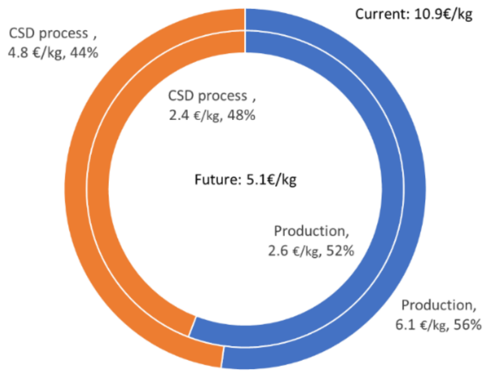


Figure 56 Real dispensing price breakdown plot of the system (Outer is current and inner is future)

The current cost price for dispensed hydrogen fuel is €10.9/kg and 56% of RDHC is for hydrogen production because the on-site water electrolysis system is used and the energy resource is from wind turbine. In the future, the production cost will reduce more than 50%, due to R&D progress, operational maturity and high-volume production. The hydrogen fuel cost price will also reduce to €5.1/kg.

These results will be discussed in the following aspects.

Hydrogen Production and Dispensing Costs

The production cost (LCOHP) in Table 10 is much higher than hydrogen produced by centralized SMR(Steam Methane Reforming) system with grid electricity[76]. The system designed in this report is an almost completely carbon-free system which leads to higher environmental benefits than SMR.

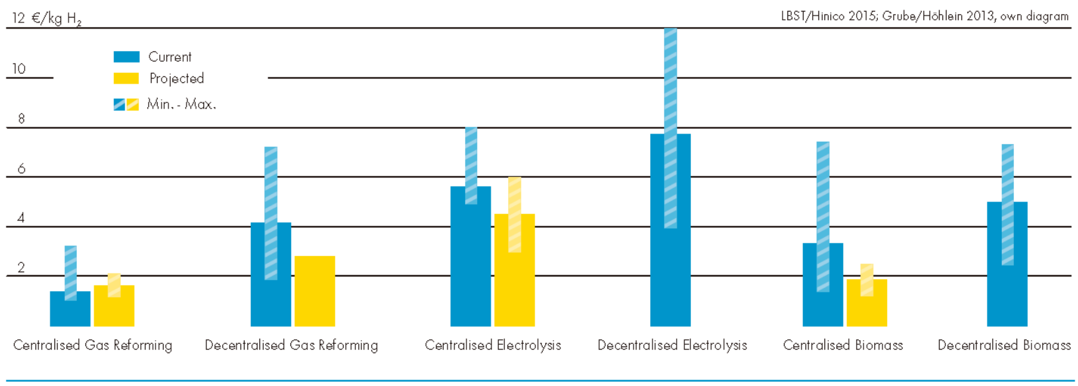


Figure 57 Hydrogen production cost based on different technologies[76]

Comparing with the study from Shell in Figure 57, the current LCOHP is about €6.1/kg, which is slightly lower than the average cost of current decentralized electrolyzer system. In the future, the production cost would reduce to €2.6/kg that can even be comparable with the hydrogen produced from decentralized SMR plant.

For the dispensing cost part, the cost for hydrogen distribution and dispensing is about €4/kg for centralized system and €5.5/kg for distributed system.[83](the distributed system does not need hydrogen distribution cost but the station equipment and operation cost are more expensive.) Thus, comparing with the result in Table 10, the dispensing cost is similar and can reduce a lot in the future.

Meanwhile, the study from McKinsey[84] shows that the price of hydrogen fuel produced by steam reforming process is €7/kg in 2020 and it will reduce to €4.5/kg in around 2045. Although the RDHC is still a bit higher than this prediction, the hydrogen produced by wind-powered distributed system is totally carbon-free so that no additional carbon tax is needed, which would be very attractive for many investors and customers.

Furthermore, the future hydrogen cost in this study is also compared with the cost prediction for on-site electrolysis hydrogen refueling station with the grid electricity as the feedstock reported by NREL[85] shown in Figure 58.

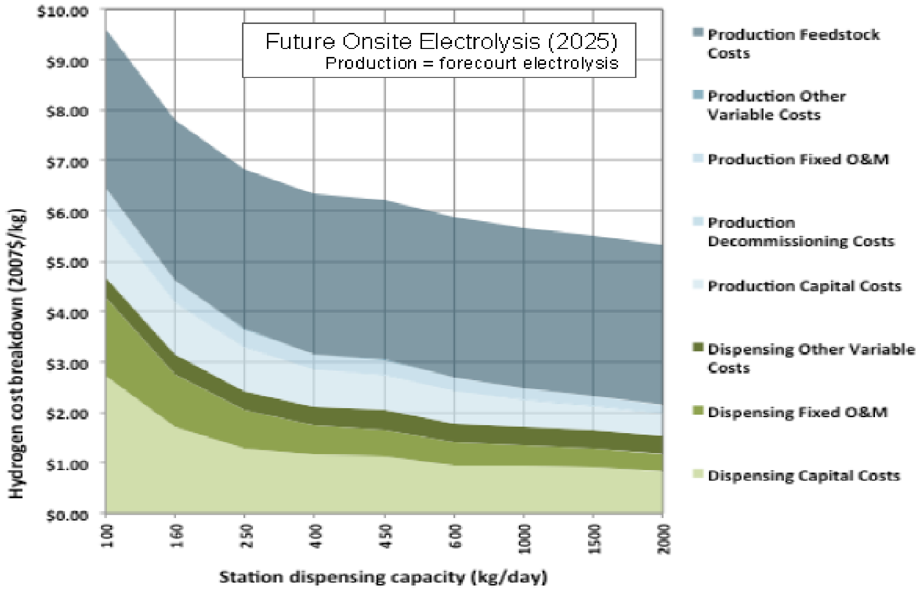


Figure 58 Cost estimation for future onsite electrolysis refueling station

For the station with the capacity of about 300kg/day, NREL indicates that the hydrogen fueling cost price is projected to be €6.3/kg in 2025, which consists of the production cost, €4.3/kg, and dispensing cost, €2/kg. Comparing with the future results in Table 10, the dispensing cost is quite similar (€2.4/kg). The study in this report uses a very optimistic cost estimation for electrolyzer so that the production cost is lower than the NREL estimation, which is €2.6/kg

Excess/Shortage hydrogen trading schemes

In the cost analysis part, the study in this report does not concern the impact because of the hydrogen trades for excess production. The cash flow from hydrogen trade would actually impact the total revenue for the system. However, the prices of selling and buying hydrogen are quite uncertain according to different condition. Generally speaking, if the selling price is higher than the LCOEP, the system can gain more profit. The best scenario should be the excess hydrogen can be sold to the other refueling station so that they can be delivered to the customers with RDHC price. It will be also discussed in the Recommendation part for the further cost reduction.

6. Conclusion

This study focuses on the design of wind-powered hydrogen refueling station modified by the existing petrol station in Germany. First, a methodology for finding the suitable stations to retrofit the proposed system is established based on the GIS data taking into account all possible restrictions. About 500 stations are selected by applying this methodology, which is about 5% of the petrol stations in Germany. Then, the system is designed and simulated based on the case study. It shows that the system can produce enough hydrogen to cover the demand for a 330kg/day refueling station with a high wind energy utilization efficiency. In the end, a cost analysis is performed, which shows a promising economic feasibility comparing with the other hydrogen production and fueling studies.

6.1 Geographic condition for the refueling station

The potential station is selected by some filters, which are created based on setback requirements and land cover condition. The results show that there are only 3000 stations away from the urban areas, which occupy about 30% of the total number of petrol stations in Germany. It means most of the petrol stations are located in the big cities or villages where are not suitable for wind turbine installation, since the wind turbine should be away from the urban areas. After filtering the stations based on land cover types, only about 500 stations are suitable for wind-powered hydrogen refueling system retrofitting.

Additionally, the selection methodology also includes some alternative filtering process. The filter based on the wind speed distribution shows that most of the potential retrofitting station are located in the area where the average wind speed is about 5-8m/s at the hub height. Another filter classifies the potential stations based on the road type nearby, which indicates that the petrol stations are usually built beside the motorway and primary road.

6.2 System design

The system from hydrogen production to dispensing is then designed for the refueling station. a large wind turbine is applied as the power supplier. All the devices are defined after a series literature reviews as well as the cost analysis. The target for this system is to fulfill 330kg/day demand and have potential for dimension upgrading.

The results show that nearly 95% of wind energy can be used to produce more than 170 tons hydrogen. The production increases to nearly 200 tons in the future because of higher efficiency of electrolyzer and compressors. On the other hand, the utilization factor for electrolyzer is about 32% because the wind turbine sometimes does not generate lots of wind energy. It means the electrolyzer has potential to be downsized in order to reduce the investment cost.

Meanwhile, with the application of pre-allocation control strategy, the wind energy can be used more efficiently. The grid consumption of system reduces from 500MWh to about 60MWh. All the low-pressure compressor demand, as well as 90% of high-pressure compressor demand, can be covered by the wind energy after the pre-allocation is used. It indicates that the extra grid upgrade cost is not necessary for the petrol station retrofitting because of tiny grid requirement of the hydrogen refueling system. The study also concerns the impact by climate variation for different years. With different years data input, the study finds that the system performance does not change too much.

Besides, only 7% of demand needs to be covered by the external supplier because of the mismatch between the hydrogen production and demand which means the cost of hydrogen delivered to the staiton is quite little. Most of the demand can be covered by the production from on-site electrolyzer, and the hydrogen production process is total carbon-free since all of the hydrogen is produced by the wind energy.

Finally, 40% of hydrogen is sold to the external communities because the on-site hydrogen production is higher than the refueling demand. For the excess hydrogen production, the hydrogen delivery can be realized by trucks or trailers with the mobile pressure tanks. In the future, a pipeline network is appreciated since it will reduce the distribution cost of hydrogen.

6.3 Economic feasibility

The cost of devices in the system are determined according to the comprehensive consideration from several references. Then the financial analysis for the whole process from production to dispensing is performed in Chapter 5.

The analysis is basically presented in two parts. The annual investment analysis converts all the capital and operating cost into annual investment via the annuity factor. It is €165000/year for current and €81000/year in the future. It shows that the investment cost almost reduces by half due to the development of all components of the system, especially for the electrolyzer, which reduces nearly 80% for its investment in the future.

The second part is the levelized cost analysis. The total dispensing price is €10.9/kg for the current scenario and comes to be €5/kg because of investment reduction in the future. This cost can be split into the cost for hydrogen production and the cost for the dispensing system. Comparing the hydrogen fuel study from the literature, the cost for the dispensing system (LCOHD) is similar to the other distributed refueling system but the production cost (LCOHP) is still higher than the hydrogen produced by centralized system in the current scenario. However, the cost will reduce rapidly in the future since the increase of volume production for the system when the niche market is established. It will lead to a high economic feasibility for the refueling system in this project.

7. Recommendation

7.1 Geographical filtering methodology

To improve the accuracy of the filtering result, some suggestion is discussed from the following aspects:

Using more raster or polygon GIS data

In the methodology establishment part, the point data and buffer area are used to filter station near the populated area, but the circular buffer cannot cover all the urban area. (most of the villages do not have a regular shape.) Thus, some of the stations at the edge of the village would not be excluded such as the one shown in Figure 59.

Figure 59 Shell station at the edge of village

In practical, using the raster or polygon data can avoid such problems as they sketch the areas of the land cover or land use, but sometimes it is difficult to find the suitable and near-term dataset for analysis. For example, the CLC dataset updates around every six years, so the latest version is from 2012. However, the urbanization is quite fast in recent years which makes the GIS data may not quite correct. On the other hand, although LOCUS data is quite new (update to 2016), it uses the point data represented the observer and transections to describe the surrounding environment, which is not practical for data analysis. To improve the accuracy of the selecting system, one more precise and updated database should be applied, or at least the field investigation should be performed.

Associating with related hydrogen project in Germany

Moreover, H2 MOBILITY project has the roadmap for station construction shown in Figure 60.

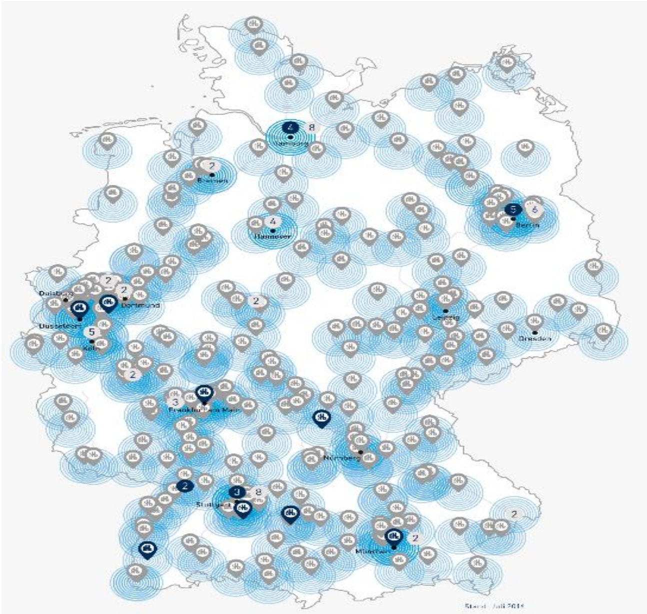


Figure 60 H_2 MOBILITY roadmap for refueling station establishment

Up to 2023, there will be 400 hydrogen refueling stations in Germany according to their plan. It would be very helpful the geographical analysis results from this report can be compared with the location where these potential hydrogen stations will be built in H2 MOBILITY. The locations where are both satisfied with the H_2 MOBILITY project and the requirements for land cover and land use can be picked out. These places would be the best choice for hydrogen refueling station establishment.

7.2 Improvement for system design

There are numerous assumptions used in this study which would reduce the accuracy of the simulation results. For the further study, a more precise modelling is necessary to reflect the operational behaviors of the wind-powered hydrogen refueling station. Here some recommendations are provided for this improvement.

More detailed data input

The study uses the constant daily demand and the wind speed data from the climate station about 5km away from the petrol station as the data input. The more detailed wind speed and demand profile input can improve the accuracy of system dynamic behavior.

The detailed wind speed data can be collected by the wind speed sensor installed near the station. In this way, the wind data with variation in second can be used for simulation. The impact of wind direction and inertia of wind turbine should also be considered.

For the demand profile improvement, the demand profile should be varied based on the local conditions. A good suggestion is to use the population density near the station to define the demand. The demand for the station can also be defined based on the traffic density of the road nearby, associated with the road type filter introduced in 2.2.5.

Other supplementary renewable technologies integration

The other kind of renewable technologies can also be integrated into the system such as solar panel or fuel cell power plant. For instance, the PV panels can provide the electricity to compensate the system demand when the wind source is not enough. It can also be used for rain water collection at the same time, which can be purified and used for the electrolyzer.

More detailed dynamic modelling of system components

In this study, many of the operational parameters are assumed to be constant. More detailed dynamic modelling is required for a more accurate model.

For the electrolyzer and compressors, applying a dynamic efficiency according to the flow rate and pressure difference in every time steps can improve their accuracy instead of the constant efficiency. The efficiency of compressor should vary with the operating pressure and flow rate, a look-up table from the manufacturer for efficiency calculation would give more practical results.

For the other components such as cooling unit for dispensing, the energy consumption also varies based on the outdoor's temperature and flow rate. These issues should be defined more precisely in the future study.

Site and demand based sizing

The study sizes the electrolyzer based on the capacity of the wind turbine. However, the wind turbine only has a 0.3 capacity factor at the case study location so that the electrolyzer cannot work at the rated capacity for most of the time.

The further study should dimension the system components more carefully. The system scale should be defined with the consideration of wind condition, available site space and the local refueling demand. If the system can be defined with the proper size, the investment of the system can be reduced further.

7.3 Possibilities for further cost reduction

Some ideas are also suggested for further cost reduction of the system.

Establishing pipeline network between several refueling stations

Although the system sizing is for 330kg/day demand, the wind turbine actually can generate enough energy to support 30% more hydrogen demand. Considering the influence of mismatch between the wind energy and demand profile, the hydrogen trade between the station and the other hydrogen supplier is necessary for the model, although it is less economical for the seller since the hydrogen market price is quite low compared with the current production cost price.

To make the hydrogen trade in a more economical way, the hydrogen pipeline network would be a good solution. In the future, with more hydrogen refueling station built, it is economically viable and practical to establish a pipeline network between several refueling hydrogen stations so that one can transfer the excess product to the other stations whose storage is not enough. It is also possible to deliver the hydrogen to the refueling station where is not suitable for wind turbine installation in the city center. In this way, all the hydrogen production can be sold at the dispensing cost and only about €0.5/kg H_2 additional cost is required for pipeline distribution[83]. This cost would reduce more if the related technology and material developed in the future.

Hybrid FCEV fueling and BEV charging in wind-powered stations

The wind energy can be stored as the electricity, too. In this way, it is also possible for charging the other kinds of EVs in the station. Since the future renewable energy vehicle market will be dominated by several types of electric vehicles such as BEV, PHEV and FCEV. The station that can provide charging service for all of the types of vehicles with carbon-free energy would be very attractive for the investors.

Appendix

A. CLC land cover types

Table 11 The land cover types sketch in the CLC map

Forests (high obstacles)	**Populated Area**
Complex cultivation patterns	Road and rail networks and associated land
Agro-forestry areas	Port areas
Broad-leaved forest	Airports
Coniferous forest	Mineral extraction sites
Mixed forest	Construction sites
Sclerophyllous vegetation	Green urban areas
Transitional woodland-shrub	Sport and leisure facilities
Appropriate Land Cover	**Improper foundation condition**
Dump sites	Inland marshes
Non-irrigated arable land	Peat bogs
Permanently irrigated land	Salt marshes
Rice fields	Salines
Vineyards	Intertidal flats
Pastures	Water courses
Annual crops associated with permanent crops	Water bodies
Land principally occupied by agriculture	Coastal lagoons
Natural grasslands	Estuaries
Sparsely vegetated areas	Sea and ocean
Moors and heathland	

The land cover types accounting in the GIS database are listed in Table 11, although some of the types do not appear in the Germany land cover map. The station chosen for system construction are all located on the grass area or crop area where there are fewer obstacles and avoid being around the urban or industrial areas. In the selection model, the land cover types in the red column are considered as the proper land cover types.

B. Wind speed calculation at hub height

In order to estimate the wind energy produced by the wind turbine, the wind speed at the hub height is derived based on the wind speed data from the meteorological station. Commonly, two formulas are introduced to calculate this, the power law and the log profile. Log profile is usually used for the low height to include the impact of surface roughness and power law is more accurate when the height is more than 100m[86][87].

The wind speed data for analysis is measured at about 10m at the station. First, the log wind profile is used to derive the speed at 100m based on the wind speed at 10m. Many report or lecture[88][89] tend to use the following formula for this calculation:

$$\frac{U(h)}{U(h_{ref})} = \frac{\ln(h/z_0)}{\ln(h_{ref}/z_0)} \tag{B.1}$$

The wind speed at height h can be estimated by the velocity at h_{ref} and the local roughness Z_0.

Then from 100m to the hub height, which is 159m in the case study model, the wind speed is calculated by the power law, which is:

$$\frac{U(h)}{U(h_{ref})} = (\frac{h}{h_{ref}})^{\alpha} \tag{B.2}$$

Where α is equal to 0.143 for the open land area in the wind resource assessment[86].

In practical, the wind data for station filtering in Chapter 2 is already at 100m height, so only the power law is applied to calculate the speed at the hub height. For the hourly data as the simulation input, both log profile and power law are necessary for hub height speed estimation.

C. Wind turbine survey

Table 12 Technical parameter of Enercon and Vestas commercial products

Enercon				
Type	Rotor Diameter (m)	Hub Height (m)	Rated Capacity (MW)	Available Wind Class
E-126 EP4	127	99/135/159	4.2	IIA
E-101	101	99/124/135	3.05	IIA
E-70	71	57/64/75/85/98/114	2.3	IA IIA
E-44	44	45/55	0.9	IA
E-141 EP4	141	129/159	4.2	IIIA
E-115	115.7	92/122/135/149	3	IIA
E-82	82	78/84/85/98/108/138	2	IIA
E-103 EP2	103	98/138	2.35	IIIA
E-92	92	78/84/85/98/104/108/138	2.35	IIA
E-53	52.9	50/60/73	0.8	S
E-48	48	50/55/60/65/76	0.8	IIA
Vestas				
Type	Rotor Diameter (m)	Hub Height (m)	Rated Capacity (MW)	Available Wind Class
V136-3.45MW	136	82/112/132/149	3.45	IIIA/IIIB
V110-2.0MW	110	80/95(IIIA) 95/110/120/125(IIIB)	2	IIIA
V126-3.45MW	126	87/117(II) 137/147(IIIA)	3.45	IIA/IIB
V100-2.0MW	100	80/95	2	IIB
V117-3.45MW	117	80/91.5/116.5	3.45	IB/IIA
V100-1.8/2.0MW	100	80(IIB)/95(IIIB)/120(IIIA)	1.8/2	IIIA-S
V112-3.45MW	112	69/94	3.45	IA
V90-1.8/2.0MW	90	80/95/105	1.8/2.0	IIA/IIIA
V105-3.45MW	105	72.5	3.45	IA
V90-3.0MW	90	65/80(IA) 105(IIA)	3	IA/IIA

D. Storage Tank Sensitivity

One of the assumptions in the simulation is the hydrogen in the backup tank can be sold to the other communities. Although the total amount of hydrogen for trades does not change because the production and demand are the same, the capacity of the storage tank and the backup tank would impact the hydrogen trades frequency and cash flow. This section will discuss the cash flow change because of storage capacity variation. Please be aware that the storage capacity mentioned below is the capacity for each tank. The system has two such stationary tanks and one mobile backup tank in the system.

Based on the current scenario, the model is simulated with a different storage tank (assuming the stationary and backup tanks have the same capacity) from 200kg to 800kg for each. the following table shows the results for hydrogen trades frequency with different capacity.

To calculate the net cash flow because of hydrogen trade, it assumes that the station can buy the hydrogen with average market price that is €4.5/kg for now and €3.5/kg in the future, and sell the product with a bit competitive price that is €4/kg for now and €3/kg in the future based on the survey from McKinsey[84].

Table 13 The summary for annual hydrogen trades with different tank capacity

Capacity (kg)	Sold (in frequency)	Sold (in mass kg)	Bought (in frequency)	Bought (in mass kg)	Net cash flow € (income)
200	375	75000	97	19400	175200
300	233	69900	47	14100	181200
400	165	66000	25	10000	186000
500	127	63500	15	7500	188500
600	105	63000	12	7200	188100
700	87	60900	8	5600	187950
800	75	60000	6	4800	188400

The impact of tank capacity change comes from two aspects. First the investment for storage tank would change. The approximate estimation for this part is about €15000/(100kg capacity) per year including the CapEx and OpEx. Another impact is the amount of cash flow because of hydrogen trades. According to the results shown in Table 13, the net cash flow variation does not always increase when the tank capacity gets bigger.

In conclusion, storage tank capacity upgrading would increase the annual system investment by about €15000/(100kg capacity), which is about €0.12/(100kg capacity) for the RDHC. However, the economic benefits because of this upgrade are not as much as the investment cost increase. It seems that the cash flow due to the hydrogen trade is always around €188000 annually. Thus, a small capacity tank is more appropriate for the system.

E. Energy consumption calculation for compressor

a constant consumption is assumed for the maximum pressure output (i.e. we assume the compressor is a steady-flow device.). For the low-pressure compressor, the output pressure is 200bar for now and 400bar in the future. The inlet hydrogen statement is 30bar with 15℃.

Then the isentropic efficiency is used:

$$\text{Isentropic Efficiency} = \frac{\text{Isentropic Compressor Work (Consumption)}}{\text{Actual Compressor Work (Consumption)}} \cong \frac{h_{2s}-h_1}{h_{2a}-h_1} \qquad \text{(E.1)}$$

For all the above equations:

h1 is the specific enthalpy at the entrance state

h2a is the specific enthalpy at the exit state for the actual process

h2s is the specific enthalpy at the exit state for the isentropic process

In the model, the inlet state is 30bar with 15℃, then by using the EES software (or looking up in the property table for hydrogen), the entropy of inlet is 55.928kJ/kg.K and enthalpy(h1) is 4070.4 kJ/kg

The isentropic process means the entropy does not change, so the outlet state is defined by the pressure and entropy. Thus, the h_{2s} at 200bar is 7199.9 kJ/kg, at 400 bar is 8923.8 kJ/kg.

The actual energy consumption is derived as:

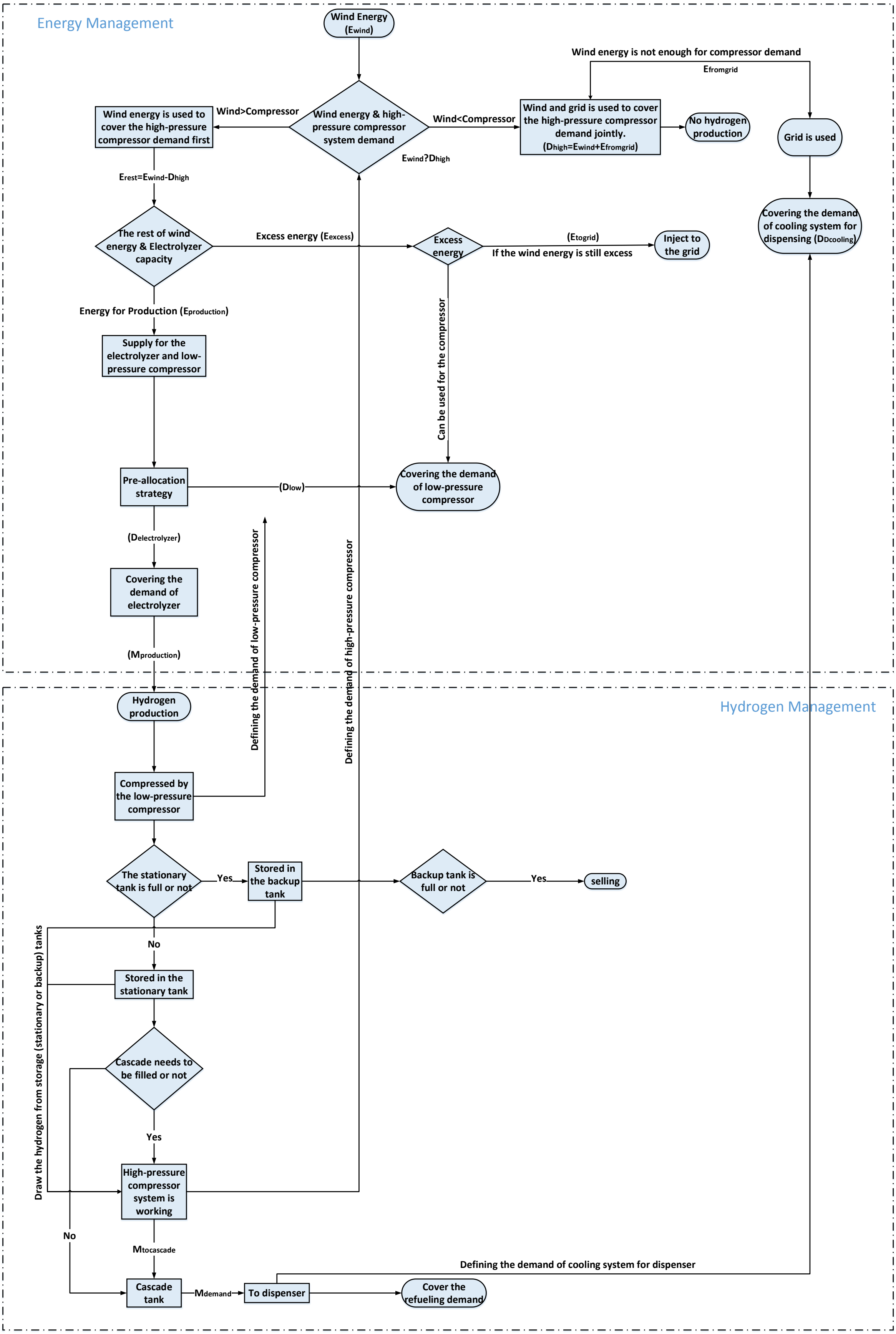
$$\text{Actual Compressor Work (Consumption)} = \frac{\text{Isentropic Compressor Work (Consumption)}}{\text{Isentropic Efficiency}}$$

$$\cong \frac{h_{2s}-h_1}{\text{Isentropic Efficiency}} \qquad \text{(E.2)}$$

The isentropic efficiency is 65% for now and 80% for future scenario.

Therefore, the consumption can be calculated as 4815 kJ/kg for now and 6067 kJ/kg for now and future. At last, since 1kWh=3600kJ, the final result is 1.3 kWh/kg for now and 1.7 kWh/kg for future.

F Control strategy flowchart and detailed explanation



Energy view

Wind energy is derived based on the wind speed and power curve. (E_{wind})

The cascade tank is checked first, if its state is lower than the set level (25kg), the high-pressure compressor is working, the demand of high-pressure compressor(D_{high}) is defined by the high-pressure compressor system consumption (C_{high} kWh/kg) and the hydrogen need to be filled to the casaced in this hour ($m_{tocascade}$)

$$D_{high} = C_{high} * m_{tocascade} \tag{F.1}$$

The wind energy supplies for high pressure compressor first, the rest of wind energy will be used for the hydrogen production (E_{rest}).

$$E_{rest} = E_{wind} - D_{high} \tag{F.2}$$

If the wind energy is lower than the high-pressure compressor system demand, the grid energy is used ($E_{fromgrid}$), and no energy will be delivered to the hydrogen production part, which means:

$$E_{rest} = 0 \tag{F.3}$$

$$D_{high} = E_{wind} + E_{fromgrid} \tag{F.4}$$

If the wind energy is higher than the demand of high-pressure compressor, which means E_{rest} is higher than zero. According to the capacity of the electrolyzer, the energy will be divided into two parts, for the hydrogen production ($E_{production}$) and excess part (E_{excess})

$$E_{production} + E_{excess} = E_{rest} \tag{F.5}$$

Then by using the pre-allocation control strategy, the energy is allocated into three parts, cover the demand of electrolyzer ($D_{electrolyzer}$), cover the demand of low-pressure compressor (D_{low}) and go to the grid (E_{togrid}).

$D_{electrolyzer}$ is defined by the energy consumption for hydrogen production ($C_{electrolyzer}$ kWh/kg) and hydrogen yield ($m_{prduction}$). D_{low} is defined by the compressor consumption (C_{low} kWh/kg) and $m_{prduction}$ (all the hydrogen need to be compressed by this compressor)

$$D_{electrolyzer} = C_{electrolyzer} * m_{production} \tag{F.6}$$

$$D_{low} = C_{low} * m_{production} \tag{F.7}$$

The pre-allocation strategy makes the follow equation is always true

$$D_{electrolyzer} + D_{low} + E_{togrid} = E_{production} + E_{excess} \tag{F.8}$$

For most of time, the E_{rest} is smaller than the electrolyzer capacity, which means no excess energy in the system. The equation above can be simplified as:

$$D_{electrolyzer} + D_{low} = E_{production} = E_{rest} \tag{F.9}$$

In the model, the demand of electrolyzer and the low-pressure compressor is calculated by using equation (F.5) to equation (F.8) with an iteration method.

The cooling system for dispenser needs the grid energy when dispensing ($D_{Dcooling}$). It is defined by the consumption ($C_{Dcooling}$ kWh/kg) and the dispensing hydrogen demand ($m_{dispensing}^{demand}$)

$$D_{Dcooling} = C_{dispensing} * m_{dispensing}^{demand} \quad (F.10)$$

In conclusion, the wind energy will provide the demand of compressor and electrolyzer. The grid is used for cooling system and supply energy when the wind is not enough. The overview energy balance is derived as:

$$E_{wind} + \mathrm{E}_{fromgrid} = D_{high} + D_{electrolyzer} + D_{low} + E_{togrid} \quad (F.11)$$

When the wind energy is lower than the demand of high-pressure compressor, no hydrogen is produced, the balance is simplified as:

$$E_{wind} + \mathrm{E}_{fromgrid} = D_{high} \quad (F.12)$$

When the wind is enough and no excess energy (such as the situation for in the case study, excess is zero)

$$E_{wind} = D_{high} + D_{electrolyzer} + D_{low} \quad (F.13)$$

The total grid consumption is:

$$D_{grid} = \mathrm{E}_{fromgrid} + D_{Dcooling} \quad (F.14)$$

When wind is enough, $E_{fromgrid}$ is zero so grid consumption is equal to the dispensing demand.

Hydrogen view

(Storage part) First, the hydrogen production will be compressed and stored in the stationary tank. If there is too much hydrogen comparing the capacity of stationary tank ($m_{stationary}^{capacity}$), the rest will go to the backup tank. The stationary storage is composed by two tanks, the detailed storage strategy for these two stationary tanks is shown in the report.

$$m_{stationary}^{state\ new} = m_{stationary}^{state\ old} + m_{production} \quad (F.15)$$

$$if\ m_{production} > \left(m_{stationary}^{capacity} - m_{stationary}^{state}\right) \quad (F.16a)$$

$$m_{backup}^{state\ new} = m_{backup}^{state\ old} + (m_{production} - m_{stationary}^{capacity} + m_{stationary}^{state}) \quad (F.16b)$$

The hydrogen in the backup tank is assumed can be sold when it is full and replaced by an empty one.

(Refueling part) Checking the state of cascade, if it is lower than the setting level ($m_{cascade}^{setting\ level}$), draw the hydrogen ($m_{tocascade}$) from the storage tanks (stationary tank or backup tank if stationary is empty) to fill the cascade to full.

$$if\ m_{cascade}^{state} < m_{cascade}^{setting\ level} \quad (F.17a)$$

$$m_{tocascade} = m_{cascade}^{capacity} - m_{cascade}^{state} \quad (F.17b)$$

Equation (F.17b) is also involved in high-pressure compressor demand determination in Equation (F.1)

(Dispensing part) The dispenser will use the hydrogen in the cascade to fuel the FCEV. Because of the control strategy in refueling part (always keep the cascade level higher than setting level, which is defined by the maximum hourly demand.), there is always enough hydrogen for dispensing in cascade.

$$m_{cascade}^{state\ new} = m_{cascade}^{state\ old} - m_{dispensing}^{demand} \tag{F.18}$$

G. Grid connection investment

In the report, the existing grid capacity in the petrol station is assumed to be large enough so that no extra cost is needed for the new hydrogen refueling station. However, a brief analysis of the grid connection investment is still presented in this section according to the information from grid operation companies.

Based on the simulation results analysis, the grid capacity requirement is about 70kW and the annual grid consumption is around 60MWh for the current scenario. This conclusion will be used to do the grid connection investment.

The cost standards come from the STEDIN and TenneT. They have the different charging modes shown in the following table.

Table 14 The grid connection cost

STEDIN (<175kVA)[90]		
	Price	Comment
Fixed Cost	€4058 per connection	€47/m if the cable required is longer than 25m
Annual Operational Cost	€67.65/year	
Total Cost	€6500	
TenneT (>2500 hour/year)[91]		
Service Cost	€103.68/(kW*year)	
Working Cost	0.22cent/kWh	

The TenneT grid cost also includes network costs which have already been included in the electricity cost[92]. To specify the cost impact of only grid connection capital, the STEDIN cost is used here. The total cost of grid connection throughout the lifetime (20 years) is just €6500. Associated with the influence of annuity factor (14.21), the additional levelized cost because of grid connection is 3cent/kg H_2 for RDHC. It is a very small part comparing with the RDHC for a current scenario that is €10.9/kg H_2.

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