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From national level to a case study in Germany

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DOI
10.1109/SEST.2018.8495693

Publication date
2018

Document Version
Accepted author manuscript

Published in
Proceedings of the 2018 International Conference on Smart Energy Systems and Technologies (SEST 2018)

On-site wind powered hydrogen refuelling stations – From national level to a case study in Germany

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***Abstract* - Hydrogen refueling stations are an important part of the infrastructural development that should be developed in order to realize a 100% sustainable economy for the future. Most of the refueling stations are located within urban areas but there are many located outside urban areas or in remote areas. Hydrogen could either be transported to these sites or being locally produced with integrated sustainable energy systems. In this study the potential number for wind powered hydrogen refueling stations using GIS is determined. Furthermore the amount of hydrogen that could be produced and used is determined via energy system simulation. Finally the hydrogen production and dispensing costs are calculated**

Keywords – Wind Turbines, GIS data, System Integration, Hydrogen refueling stations, Case study, On-site hydrogen production

I. Introduction (How could an on-site wind powered hydrogen refuelling station look like?)

One of the many methods to make hydrogen is to utilize electricity from wind turbines and feed it in electrolyzer to produce "green" hydrogen. Having all the systems that contribute to hydrogen production within the administrational boundaries of the refueling station pose an interesting case with potential cost reduction due to the proximity and the elimination of interconnection to the existing electrical grid since all wind turbine electricity is being converted to hydrogen fuel. From a technical perspective, a large wind turbine is connected with an inverter to a large scale electrolyzer who produces "green" hydrogen and through a low pressure compressor coupled with this system it pumps the produced hydrogen in 200 bar storage buffer tanks. A high pressure compressor coupled with the existing connection to the local electricity grid in order to ensure at all times that there is possibility to refuel a hydrogen powered vehicle. This parallel system compresses hydrogen to the dispensing buffer of 900 bars. The excess hydrogen that is stored in the low pressure tanks is assumed to be sold to nearby urban or rural areas for various types of demand either with tube trailer transport or if there would be a hydrogen gas pipeline network to be fed in it.

The system described in Figure 1 will be modelled and assessed in the following paper through:

- a GIS (Geographics Information systems) study of the potential of existing fueling stations to be converted in Germany
- a case study in order to understand the system operational and economical ranges.

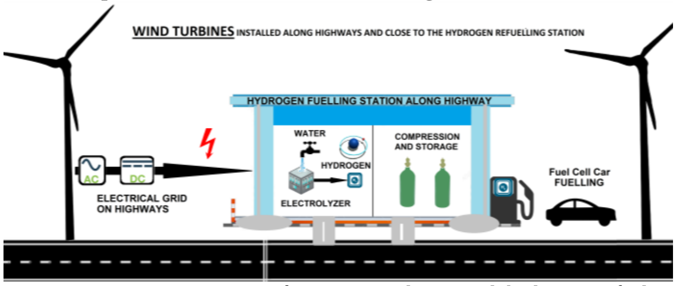

Figure 1 : System overview of on-site wind powered hydrogen refueling station

II. GIS study (The national potential for on-site wind powered hydrogen refuelling stations in Germany)

There are 10518 existing fuelling stations in Germany [5] as the following map indicates. However, not all of them could host a wind turbine system. For example, a large wind turbine cannot be installed within an urban city landscape or next to an airport. This study uses GIS big data for the country of Germany to examine how many of the existing stations could host a wind turbine close by, in order to economically utilize the electrical energy for hydrogen production.

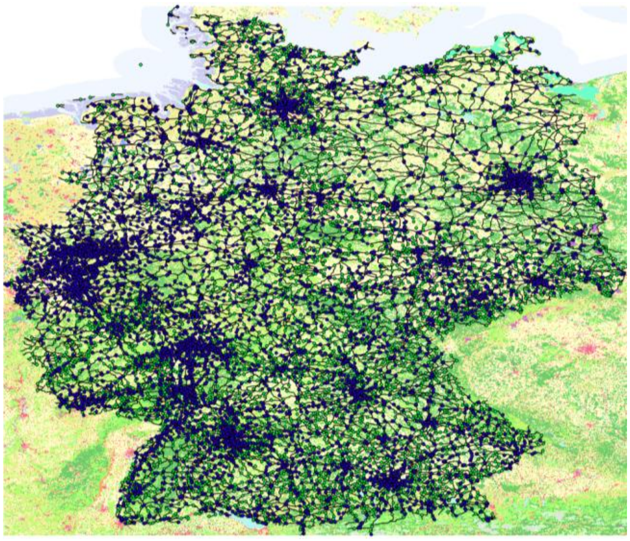

Figure 2 : Map of Germany showing the petrol stations available (blue dots) and the existing road network

A. *The GIS filters applied*

Several databases have been used within a GIS software in order to determine the amount of stations that are suitable and have potential to utilize wind turbines to provide electricity to produce locally the "green hydrogen". All the filters have been assessed through geoprocessing tools, linestring and polygon comparisons within QGIS programme. A buffer area around each existing fuelling station has been considered in order to filter out the fuelling stations that do not fulfil the following criteria:

- Setback distance from populated areas using EuroGeographics database [2] polygon and linestring data
  - 500m away from urbanized areas
  - 1500m away from small village centre-point
- Circular Buffer zone of 500m away from eco-protected areas which are represented with point observations through the LUCAS database (Land Use/Land Cover Area Frame Survey) [1]
- 2000m away from airports
- Avoidance of forest areas as categorized in the 2012 Corine Land Cover Database [3] (for example, coniferous forests, agro-forestry areas)
- Avoidance of areas with improper foundation conditions as categorized in the 2012 Corine Land Cover Database [3]
- Wind resource potential lower that the IEC (International Electrotechnical Commission) Class IV turbine based on wind speeds at hub height of 150m with data used from reanalysis datasets from the ECWMF (European Centre for Medium-Range Weather Forecasts) [6]

The following figure is a good example of the filtering procedure. In the centre image the large grey area indicates the urbanized zone, the purple circles indicate the buffer zone around urbanized areas (settlements/villages) and the small green points indicate the fuelling stations. On the left part of the image you can observe the fuelling stations (green points) within the urban area (grey area), while in the right picture the filter has been applied.

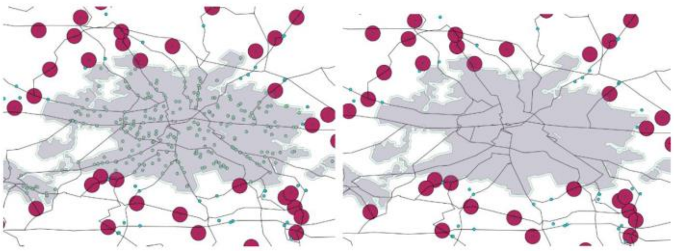

Figure 3 : The filtering process

B. *Results of the GIS study*

Out of the 10.518 stations nearly 70% are located very close to inhabited areas making them unsuitable for wind turbine installation.

A further filtering on these 2998 stations based on ecological and airport limitations leaves us to 2577 stations.

After that the land cover filter for improper foundations and forests (high obstacles) leaves it to 525 stations are left.

The assessment results indicate that 3.6% (380) of all the refuelling stations in Germany (10500) could host a wind-powered hydrogen production and refuelling station and are in the IEC Class IV turbine classification [6] for hub height of 150m and the rest 1.4% are on the other classes.

A further post-analysis with respect to the road type proximity of the fuelling station leads to the following (some stations can fall in 2 categories than one)

- 195 stations on primary routes
- 133 stations on national motorways
- 68 stations in secondary routes
- 7 stations in local routes
- 165 stations in unclassified routes

This post-analysis indicates that most of the fueling stations are located on primary routes or national motorways. This is relevant for further considerations into the national road-mapping this particular system for hydrogen infrastructural development.

The main conclusion of this study is that there are 5% of fueling stations in Germany that are suitable for on-site wind powered hydrogen production and dispensing. Therefore this will lead us to the next chapter of designing a case study.

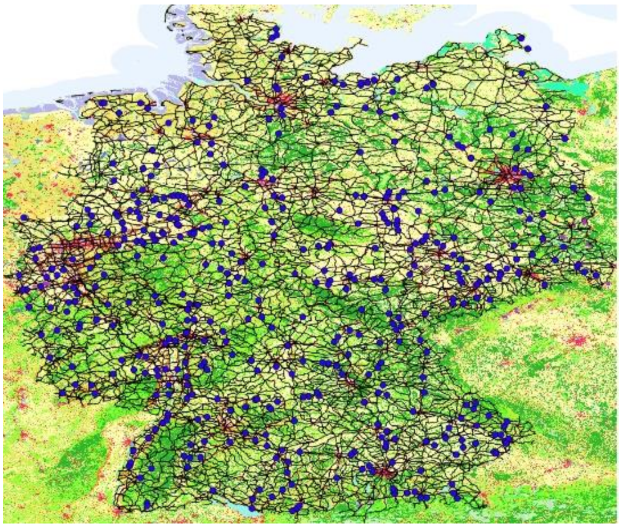

Figure 4 : Map of Germany with the filtered petrol stations that are suitable for wind turbine installation (blue dots)

III. A Case Study for the System proposed

The GIS study has led us into designing a case study for these fuelling stations in order to assess its technical and economical parameters. The location of the case study is the mainland of Germany with the following coordinates (50.0574N, 8.449E). The wind speed local climate characteristics are taken from the Climate Data Center of Deutscher Wetterdienst [7] from a local weather station (5km away) and have been corrected for the hub height and roughness of the fuelling station location.

An energy system simulation with MATLAB has been performed to estimate the amount of hydrogen that could be generated with the proposed system.

A fully integrated system with the following components has been simulated:

- E-141 EP4 wind turbine 4.2 MW [9] [10]
- 3 units of the 1.25MW Silyzer 200 PEM electrolyzer with a rated output of 65kg/h [11],
- Two stationary low pressure hydrogen tanks at 200bars (400kg of hydrogen each) [12]
- One mobile backup tank at 200 bars (400kg of hydrogen)
- High pressure compressor (33.6kg/h based on an industrial product of Linde) [12] [13]
- Two dispensers (3.6kg/min based on an industrial product of Linde) [12]
- Cascade tank (100kg)
- A representative fuel cell vehicle hydrogen demand based on current fuel consumption data for normal petrol cars

The aforementioned system is visualized with the following figure:

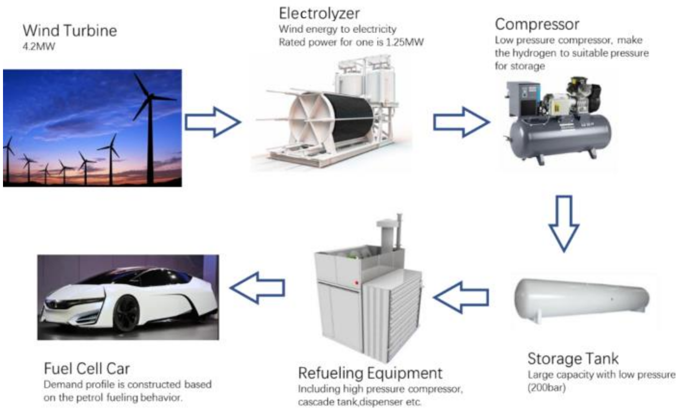

Figure 5 : Modelled system

An important parameter of the modelling is the refueling demand of the future fuel cell electric passenger vehicles (FCEV) that will visit the fueling stations to fuel up with hydrogen. The following figure represents the average annual hourly demand of hydrogen for the 330 kg/day fueling station to be designed (65 cars per day). This is determined from assuming a 20-40% FCEV drivetrain scenario for the future and an average visit of 200 vehicles per station [15].

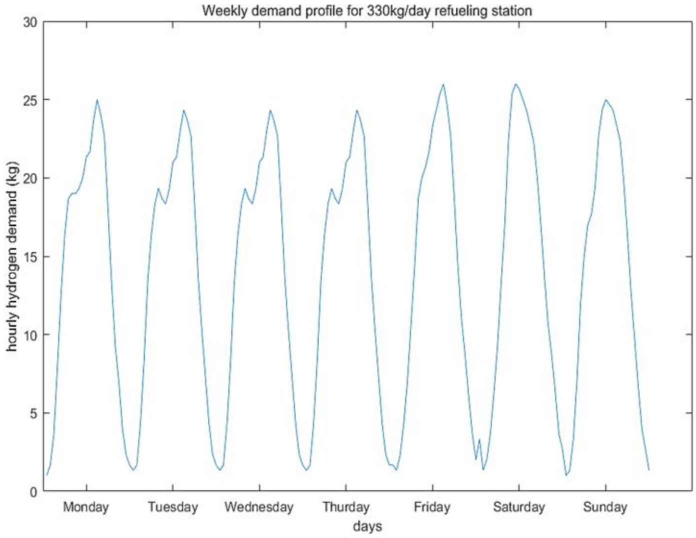

Figure 6: Hourly hydrogen demand profile for an entire week

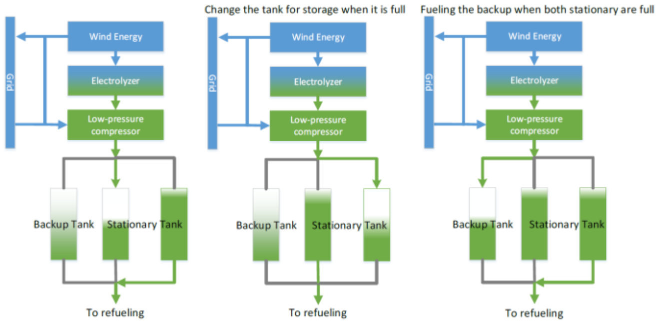

Figure 7: Control logic for the storage

In figure 6 above you can see the flow of electricity with blue color and the flow of hydrogen with green color. In the figure 7 below, you can see the flow of hydrogen from the storage tanks to the high pressure compressor with green color and the orange color indicates the hydrogen flow to the cascade system, responsible for the refueling of the FCEV tanks. The cascade is 30kg and it should always contain 25 kg in each time step in order to ensure the ability to refuel the maximum hourly demand of 5 cars per hour (25kg hydrogen).

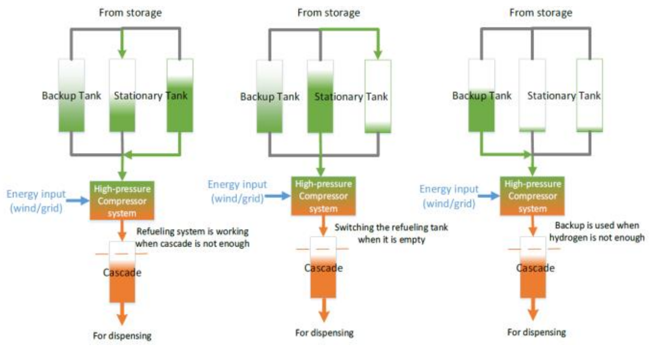

Figure 8: Control logic for the refueling

A. *Results of production possibilities*

It was shown that in a continuous operation, the station can cover 92% (110 tons) of the car refueling demand with locally produced and stored hydrogen fuel and the rest 8% (10 tons) is covered by external hydrogen fuel purchases throughout a full year.

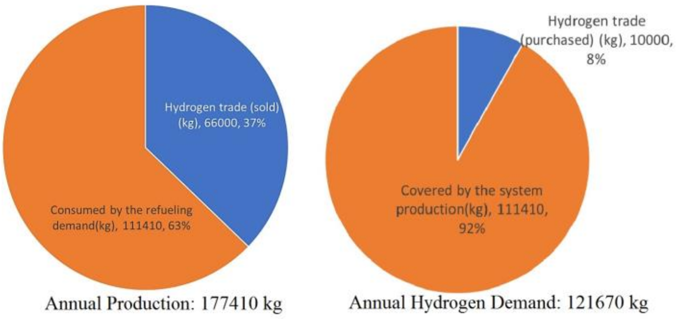

Figure 9 : Hydrogen demand and production system-related characteristics

Moreover, the 60% (111 tons) of the wind powered hydrogen production is locally stored and dispensed while the rest 40% (66 tons) is being exported. The figure below shows the frequency of tube trailer refill whether selling or buying hydrogen per month.

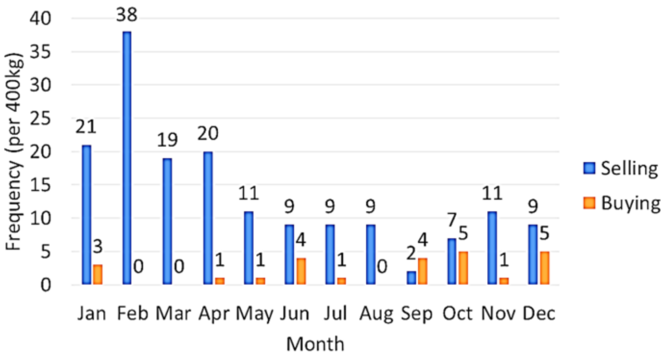

Figure 10 : 400kg tube trailer refill frequency per month

B. *Duration curves and capacity factors of the system*

The wind turbine capacity factor is around 30% which is a typical value for an onshore wind turbine of this size and local wind energy potential in the mainland of Germany. The capacity factor is defined as the ratio of the wind turbine annual energy yield (MWh) divided with the product of 8760 hours of a year and the rated output of the wind turbine.

Additionally the utilization factor of the electrolyzer is 32%. The utilization factor is defined as annual energy consumed by the electrolyzer (MWh) divided by the product of 8760 hours of a year and the rated power of the electrolyzer system.

By observing the duration curve of the electrolyzer in figure 11 we see that

- 1200 hours of the year (14%) the electrolyzer operates above the 80% of the electrolyzer's rated capacity
- 2300 hours of the year (26%) the electrolyzer operates between 25-80% of the electrolyzer's rated capacity
- 5260 hours of the year (60%) the electrolyzer operated between 0-25% of the electrolyzer's rated capacity

These results indicate the need to size the systems in a way that the utilization factor of the electrolyzer can be increased so that the system economics are improved and the system is not oversized.

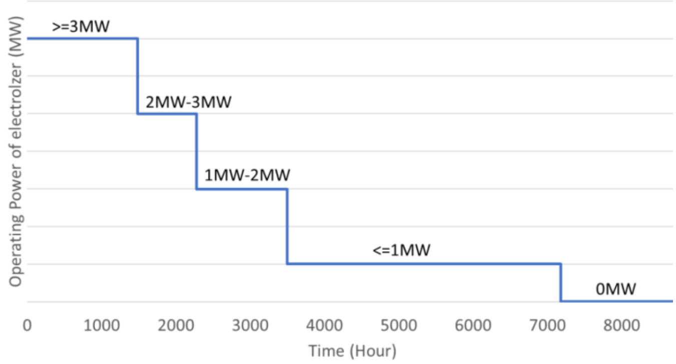

Figure 11: Duration curve of the PEM Electrolyzer

Finally, we can say that the aforementioned system can cover all the needed demand (60% of production) and export (40% of production) the excess hydrogen, giving large potential for being a hydrogen producing unit for the needs of other urban located fuelling stations.

IV. COST ANALYSIS OF THE PROPOSED SYSTEM

A techno-economic analysis has been made taking into account prices of all the components led to a cost determination of the hydrogen production [4] and dispensing. The price is expressed into (€/kg) terms taking into account a 20-year lifetime of the project and the WACC for the renewable energy investments in Europe [16].

In order to calculate the economic term of €/kg the total expenditures over the lifetime of the project had to be considered and were assumed from several references for 2 scenarios, a current one and one with future predictions.

The CAPEX and OPEX of all the systems and components have been summarized in the abovementioned table with all prices assumed from the following references [17] [18] [19] [20] [21] [22] [23] [4].

In order to quantify the cost of the hydrogen produced the following terms were used. However, they do not include the services cost of the fuelling station (e.g. land leasing cost, personnel to operate the fuelling station etc.):

- LCOHP – The Levelized cost of hydrogen produced. Which takes into account the following cost components:
  - CAPEX and OPEX of wind turbine and electrolyzer systems
  - Annual Tap Water consumption
  - Total Hydrogen produced throughout a year (kg)
- LCOHD – The Levelized cost of hydrogen dispensed. Which takes into account the following cost components:

- CAPEX and OPEX of compressor, storage and dispensing equipment
  - Annual grid costs
  - Total Hydrogen produced throughout a year (kg)
- RCHD – Real Cost of Hydrogen Dispensed, which is the sum of the 2 aforementioned costs.

TABLE 1: CAPEX AND OPEX SUMMARY OF ALL SYSTEM COST COMPONENTS

System	Cost Summary				
	Capital		***O&M***		***Comments***
	Now	Future	Now	Future	
Wind Turbine	1100 €/kW	800 €/kW	60 €/kW/year	46 €/kW/year	Installed Capacity
Electrolyzer	1200 €/kW	250 €/kW	2.5%		Installed Capacity (15% of cost for 1 replacement)
Storage Tank	870 €/kg	500 €/kg	1%		
High pressure-tank (cascade)	1180 €/kg	610 €/kg	1%		
Low-pressure compressor	6500 €/kg H_2/h	3600 €/kg H_2/h	4%	2.5%	One replacement considered
High-pressure compressor	20800 €/kg H_2/h	9600 €/kg H_2/h	4%	2.5%	
Dispenser	130000 €/unit	104000 €/unit	1.2%		One replacement considered
Pre-cooling for refuelling	155000 €/kg H_2/h	124000 €/kg H_2/h	2%		One replacement considered

But before presenting the results of the hydrogen fuel, the annual capital breakdown is summarized in the following pie chart figure. The following remarks have been made:

- Current
  - 35% of costs come from Wind
  - 28% of costs come from the Electrolyzer
  - 30% of costs account for Compressor/Storage/Dispensing
- Future
  - 50% of costs come from wind
  - 10% come from Electrolyzer
  - 30% come from Compressor/Storage/Dispensing

It is very clear that the future forecasts of price reduction in Electrolyzer have a great impact into the annual capital breakdown.

The benefit in economic terms with installing a wind turbine in the vicinity of the fuelling station and utilizing the largest part for the hydrogen production is that grid interconnection costs are minimized and usually these take about 10% of a typical onshore installation.

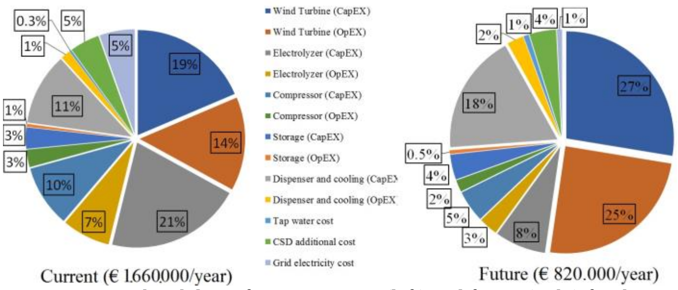

Figure 12: Cost breakdown for current time (left) and future (right) for the on-site wind powered hydrogen refueling station

With present prices, hydrogen could be produced for 6.1 €/kg with dispensing costs of 4.8 €/kg while with future projected prices hydrogen could be produced at 2.4 €/kg and dispensed at 2.4 €/kg. This is a very important outcome if we compare Huyndai ix35 (2013 model) which has a combined New European Driving Cycle (NEDC) for of 6.8liters/100km [25] while it's nearly equivalent ix35 FCEV has 0.85kg/100km [24]. If we take into account current prices of petrol in Germany which are 1.2-1.7 €/liter of unleaded petrol fuel [26] it results into 8.5-12€/100km while the FCEV fuelled up at the on-site wind powered hydrogen fuelling station is at 11€ for 100km. This result gives us a very promising future scenario. However, we should note that the service costs of operating the fuelling stations have not been considered in this study which would influence the price per kg.

TABLE II: LEVELIZED COSTS OF HYDROGEN PRODUCTION (LCHOP), HYDROGEN DISPENSING (LCHOD) AND TOTAL (RHDC)

	Now	Future
LHOHP (€/kg)	6.1	2.6
LHOHD (€/kg)	4.8	2.4
RHDC (€/kg)	10.9	5

V. CONCLUSIONS-RECOMMENDATIONS

As highlights of this research subject, these are:

1. GIS data showed that there are 5-10% of fuelling stations that have a potential to be converted as on-site wind powered hydrogen refuelling stations in Germany
2. The current system design and sizing leads to 60% hydrogen consumed locally at the fuelling stations while the rest 40% is being exported. This creates two recommendations.
   a. Investigate scenarios of importing this excess hydrogen to fuelling stations within the urbanized areas
   b. Design a sizing methodology and customize industrial products to match better demand without over-producing
3. The utilization factor of the electrolyzer is rather low at 30%, as well as the duration curve results indicate that the electrolyzer is over-sized leading to higher costs

4. In the present, hydrogen at these stations could be produced at 6.1 €/kg and dispensed at 4.8 €/kg with a total price of around 10.9 €/kg. This price is comparable is €/100km values with current unleaded fuelled drivetrains, but further research should be done to consider the service costs as well for the hydrogen fuel price.
5. In the future, production could be as low as 2.6 €/kg, dispensing at 2.4 €/kg thereby resulting in a price of around 5 €/kg.

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ACKNOWLEDGEMENT

This work is being granted by OpenTechnologieProgramma DUCT4U project (12728) of STW (The Netherlands)