Hydrogenation of road transport on the example of Sweden and Poland

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Abstract. The article analyzes the activities within the EU and national concerning the introduction of hydrogen fuel in road transport. The advantages and disadvantages of this drive were addressed. A directional program of hydrogen propulsion technology motion was presented on the example of Sweden and Poland. The most recent activities in Sweden regarding the so-called Nordic Hydrogen Corridor European Project. The location of basic hydrogen refueling stations in Poland until 2030 was proposed (HIT-2 Corridors European Project). These stations should be located in both TEN-T corridors running through Poland, i.e. in 1 - Poznan 2 - Warsaw, 3 - Bialystok, 4 - Szczecin, 5 - the Lodz region, 6 - the Tri-City region, 7 - Wroclaw, 8 - the Katowice region, 9 – Krakow, to ensure the possibility of passing vehicles equipped with fuel cells (FCEV - Fuel Cell Electric Vehicle) among others between Western Europe and Scandinavia.

1. Introduction

With 125 operational hydrogen refueling station (HRS) Europe has currently (September 2017 status) the largest network in the world. The network will expand to 350 hydrogen stations (already planned and financed) by 2020, which is shown on the Fig. 1 [1].

These stations require a basic demand for hydrogen from fuel cell electric vehicles to cover their operational costs and on longer term get a return on investment. The current fleet of about 500 fuel cell electric cars and 125 fuel cell buses is far too small to cover the operational cost of the existing 125 stations. Each station needs at least 100 fuel cell cars to cover running costs.

The Connecting Europe Facility (CEF) programme has co-financed 10 projects, which together deploy 77 hydrogen stations. The 10 projects represent an investment of 166 million Euro in hydrogen mobility.

Together with private, national and other European funding the CEF financing has been instrumental to setup a first hydrogen infrastructure in this transition phase in which substantial demand from fuel cell electric vehicles is not yet place. Once tens of thousands of fuel cell electric vehicles are deployed in Europe hydrogen mobility can enter a more commercial scale up of the roll-out.

Total number of hydrogen stations in Europe in context conservative estimations of numbers of fuel cell cars and buses in Europe are presented on Fig. 2.
2. EU policies on alternative fuels for road transport

As stated in the Europe 2020 strategy, recalled in the Commission’s "Clean Power for Transport (CPT): A European alternative fuels strategy” (COM (2013) 17 final, 24 January 2013), union aid shall support studies addressing technologies that reduce external costs, including mitigation and adaptation to climate change in the areas of freight and/or passenger transport [2]. A specific objective shall be the development of the necessary TEN-T infrastructure and facilities that will support the use of alternative fuels and propulsion replacing fossil fuels, including, electric propulsion of any type, hydrogen and methane.

The European Directive 2014/94/EU on the deployment of alternative fuels infrastructure (AFID), is the result of the CPT strategy [3]. It required Member States to develop national policy frameworks for the market development of alternative fuels and their infrastructure by November 2016. Hydrogen is mentioned as an option for realising zero-emission transport, especially for the longer distances, and then hydrogen infrastructure coverage of appropriate number of fuelling points by 2025 is set as an important condition.

Figure 1. Hydrogen refueling stations in EUROPE (September 2017 status) [1]

For example, the Nordic Hydrogen Corridor European Project corresponds to linked EU-directives and strategies [4]. As part of a larger package of measures to mitigate climate change, the EC has indicated the need to reduce CO₂ emissions in the transport sector by 60% in 2050 compared to the level in 1990. In order to meet these decarbonisation targets of transport, new technologies will be needed, which at the same time stimulates a shift towards cleaner and more sustainable transport in urban areas (EU Urban mobility package, 17 December 2013), which is a solution for cities to ban
polluting vehicles (Air Quality Directive (2008/50/EC)) [5] and support the Fuel Quality Directive (2009/30/EC) [6] that strives to lower carbon intensity of fuels and the Renewable Energy Directive (2009/28/EC) [7] that wants to accelerate implementation of renewable energy in fuel. The new National Emissions Ceilings (NEC) Directive that entered into force 31 December 2016 [8]; the main implementing measure is the National Air Pollution Control Programme, which the Member States must produce by 31 March 2019 [8]. The NEC Directive sets maximum emission ceilings for each country per year for fine particulate matter (PM2.5), SO₂, NOₓ, NH₃ and non-methane volatile organic compounds.

3. Deployment of hydrogen infrastructure and competitiveness of FCEV
In Europe, Germany is leading the way with the Clean Energy Partnership and the industry “H2 Mobility Deutschland” initiative, aiming to have 100 HRS in operation in Germany by 2017 and 400 HRS by 2023. The UK-H2Mobility partnership plans to have 65 HRS ready by 2017. The AFHYPAC association is working on an HRS network in France. The Scandinavian Hydrogen Highway Partnership (SHHP) is developing HRS networks in Denmark, Sweden and Norway, but only five stations are operational in Sweden now and one more will open early 2017. The Nordic Hydrogen Corridor Project will lift Sweden to the same level as neighbour countries Norway, Denmark and Germany and thereby effectively connect the HRS networks in the region and expand hydrogen electromobility in Europe. That interconnected European network will put Europe ahead of the HRS networks in Japan and USA, which are competing for leadership on FCEV, HRS and hydrogen production.
Such a “transnational European HRS network” can be used by politicians of different Member States to openly support stronger incentives to facilitate the introduction of FCEVs in their own MS and across Europe. The expansion of the European network and stronger political support and incentives in MSs are essential prerequisites for the European vehicle production sector to earlier shift of their production to FCEVs (instead of fossil fuel vehicles) and to put priority on delivering FCEV fleets to the MSs with HRS networks. European car manufacturers produce and sell cars across the world and need active support from multiple MSs to be able to prioritise deployment in Europe.

Unit costs (CAPEX) and operational costs (OPEX) are going down faster than for other propulsion systems and infrastructure, due to ongoing global optimisation of technology for HRS and FCEV; increasing growth in numbers of FCEV and HRS and further consolidation in fuel cell production (large car manufacturers start joint venture fuel cell production plants). Already now, FCEVs can be ordered from Hyundai, Toyota, Honda and Renault/Symbio FCell. The initial demand is much larger than expected: Toyota received approximately 1,500 orders in the first month of sales of the Mirai fuel cell sedan in Japan only, and subsequently decided to faster increase the production from 700 FCEV/year in 2015 to approximately 30,000 by 2020. Toyota estimates that the price of a FCEV car will be similar as for hybrid vehicles in 2020 and expects that cars running on conventional engines will have virtually disappeared by 2050. Hyundai has started production of new FCEV model NEXO with a range of 800 km and a price of circa 58,000 Euro (net price in Germany, April 2018). Mercedes has introduced the new GLC F-cell plug-in hybrid SUV, which has a 440 km range on hydrogen. Compared with the B-Class F-CELL, which has been on the market since 2010, the overall drive system offers around 40% more output; the FC system is around 30% more compact than before and the use of platinum has been reduced by 90%.

The majority of the large car manufacturers will introduce serial produced FCEVs before 2020; other brands to follow are Nissan, BMW, Ford and Audi/VW. In parallel FC buses (Van Hool, Solaris, VDL, Daimler, MAN), trucks (Nikola 1), utility vehicles, boats and trains are being introduced. At the World Economic Forum in Davos 17 January 2017, the new “Hydrogen Council” was launched by 13 leading energy, transport and industry companies confirmed their ambition to accelerate their significant investment in the development and commercialization of the hydrogen and fuel cell sectors. In the KPMG Global Automotive Executive Survey 2018 among 900 business leaders in the automotive sector the highest ranked key trend was FCEV, that is before digitalisation and battery vehicles [9].

4. Hydrogen mobility in Sweden

Following years of studies and experiments the first Swedish public hydrogen refuelling station was launched in 2014 in Malmö. In 2015 the next two hydrogen refuelling stations were opened under the
HIT-2 Corridors project – in Stockholm and Goteborg. Those stations serve a fleet of over a dozen so of hydrogen-fuelled vehicles, mostly Hyundai ix35 and Toyota Mirai.

By 2020 further 14 hydrogen filling stations will be built – among others in Sandviken, Sundsvall, Östersund, Arjeplog, Umea, Pitea (allowing for a hydrogen corridor with Finland) and Örebro, Marcestad, Jönköping, Falkenberg, Stenungsund, providing service for the most populated areas in Sweden and also for trans-European routes to Denmark, Germany and the UK [10].

In 2030 Sweden should have some 130 - 140 hydrogen refuelling stations to serve from 50 to 100,000 vehicles and approx. 50 - 100 hydrogen-fuelled buses [10].

According to forecasts for year 2050 the number of Swedish hydrogen refuelling stations should total approx. 100 objects serving roughly 2 million hydrogen-fuelled vehicles [10].

FCEVs have reached such a technological maturity that they are ready for commercialization. Market development rather than technology development is currently the main barrier for the market introduction of FCEVs. A key driver to ramp up the numbers of series produced FCEVs is the prospect of selling them, which is mainly depending on a) vehicle price and visibility; b) fuel cost per km; c) an initial network of HRS to be able to refuel within reasonable distance anywhere in Sweden and d) a strong political regulatory framework that awards FCEV effective benefits for its zero-emission performance. The inter-dependency between building a basic HRS network and serial production of FCEVs to reach competitive vehicle price levels is a typical chicken-egg problem which is currently hampering a commercial introduction.

The four drivers to reach mass roll-out of FCEVs are elaborated here for the Swedish market in specific:

a) The extent of basic coverage needed by an initial network of HRS is hard to define. Installing a hydrogen dispenser at 5% of the current number of fossil fuel stations in Sweden would be sufficient to secure availability of hydrogen across the country and for a market share of FCEV of that allows for a vehicle price compatible to comparable fossil fuel vehicles. There were 2,670 petrol stations in Sweden by the end of 2015 (Swedish Petrol and Biofuel Institute (SPBI)). A basic coverage of 5% of the current number of petrol stations would mean 1 HRS per 20 petrol stations and in total 130 HRS in Sweden. Based on previous introduction of ethanol and biogas, with such density the chicken-egg barrier has been cracked and private players have taken over the roll-out and turned it into a fully competitive and commercial market.

b) Hydrogen can be produced sustainably from a wide range of resources such as renewable electricity (cheap in periods of excess wind and solar electricity), biomass, waste and as industrial by-product. Hydrogen can store energy and thus balance the electricity grid loads while at the same time secure supply of fuel at EU-level and locally where it is produced. On a global scale, the hydrogen volumes needed for a FCEV fleet of a few percent of the total vehicle fleet and the need to store increasing amounts of intermittent energy as hydrogen, will lead to a major cut in hydrogen production costs through the market pull for more efficient technology in combination with more and larger scale production plants. In order to secure enough hydrogen for 130 HRS in Sweden the production capacity needs to be gradually expanded. Across Sweden a number of large scale plants dedicated to producing hydrogen for the HRS network is needed to reduce the fuel price.

c) Previous hydrogen mobility projects in Sweden have delivered studies, plans, a handful of HRS and tens of FCEVs. The price of the first FCEVs was above 100,000 Euros. In the next two years the price is expected to drop to around 45,000 Euros. That is only slightly more than the current price of a plug-in hybrid, which delivers a comparable range but only 40 km of electric driving. Although all previous and ongoing projects have made efforts to reach the communication target groups in Sweden - politicians, policy makers and car drivers – do not consider FCEVs as a viable new car option for the coming five years. They are not aware that FCEVs are technically ready or think that it will take at least ten more years. To raise the awareness and confidence in the viability of FCEVs as their first zero emission vehicle by high visibility of fleets of FCEVs in
the larger cities of Sweden is needed. Most people are not convinced by a marketing FCEV or articles but do believe it if they know see more of these FCEVs in daily traffic.

d) Zero tailpipe emission, no engine noise and much better environmental performance distinguishes FCEVs from conventional cars, which is by many end-users perceived as benefits that belong to the public domain. The challenge for market success is how these “public benefits” can be translated into advantages for the individual end-users. The answer is policy measures that directly benefit FCEV users. This can be subsidies, tax benefits and other options that positively discriminate zero emission and less noisy vehicles, such as parking privileges, special driving lines, city congestion toll exemption, exemption in Low Emission Zones and for night-time delivery, first place in the taxi cue, etc. Effective and long term policy and financial incentives for FCEVs and HRSs in Sweden are needed to build up a basic network of HRS until a critical number of FCEVs have been established. During the introduction phase of any alternative fuel, the investment costs for the stations cannot be covered simply by operational revenues. For HRS that is also true, as described in the FCH-JU study “A roadmap for financing hydrogen refuelling networks – creating pre-requisites for hydrogen based mobility.”

On a more general level hydrogen mobility contributes to reducing greenhouse gas emission of the Swedish transport sector. At the same time, it addresses the issue of bad air quality in urban areas in Sweden, by providing zero emission transport by FCEVs. Furthermore, the hydrogen mobility addresses the issue of creating a more sustainable circular economy. The shift to renewable hydrogen produced in Sweden and the development of key FCEV components will create new jobs for a sustainable economy in Sweden. There are a number of Swedish companies that have developed innovative technology for hydrogen production from various feedstocks. Internationally operating companies such as Sandvik and Powercell have leading edge fuel cell products in the market already. New we have opportunities for Swedish vehicle producers (i.e. Volvo, Scania, NEVS) and component suppliers.

An initial network of 130 HRS in Sweden along TEN-T core network roads for FCEV mobility by 2030, equals 1 HRS per 20 current fossil fuel stations (HRS at 5% of total number of stations). That would overcome the threshold for full commercial self-enhancing roll-out with FCEV and hydrogen at competitive prices compared to conventional vehicles. It would kick start the demand for FCEVs which in its turn should result in a further expanding number of HRS, growing numbers of FCEVs, more different FCEV models and lower prices for FCEV.

Realisation of 130 HRS in Sweden by 2030 means an investment of about 100 million euro (average 750,000 Euro per HRS, taking into account that unit costs gradually go down in that period).

The current HRS networks in the Nordic countries are shown by the green dots on the Fig. 3. With the SHHP, Sweden, Denmark and Norway have joined forces to strengthen the further development of hydrogen mobility in their countries and to create one large market with more attractiveness for deployment of FCEV fleets. SHHP has become well-known as frontrunner in hydrogen mobility in Europe.

Over the last decade, several fuel cell and hydrogen projects and market studies throughout Europe have demonstrated technical and economical feasibility and established the European industry’s role as a potential market leader in several critical areas of fuel cell and hydrogen production and distribution development.
The currently available hydrogen production capacity in Sweden is consisting of:

- The production flexibility of hydrogen plants for large industry clients; the margin between intermittent demand and the maximum capacity is used to produce hydrogen for transport.
- The hydrogen produced as by-product of production of other chemicals or remaining from other industrial processes.

End 2017 some 35 FCEVs were registered and in use in Sweden.

Nordic Hydrogen Corridor European Project is a real-life trial of 8-10 new hydrogen refuelling stations (HRS), hydrogen production units (electrolysers) and 100 – 150 fuel cell electric vehicles (FCEV) along the TEN-T Scandinavian-Mediterranean core network corridor in Sweden during the period 2017-2020 (Fig.4) It can be seen as the puzzle piece that interconnects the existing HRS networks in Norway, Denmark, Sweden and Finland. The project will create one Nordic HRS network in the most populated parts of these countries connecting the capitals Oslo, Stockholm, Helsinki and Copenhagen enabling hydrogen mobility for 18 million people across borders. Furthermore, it will facilitate hydrogen based transport in a larger part of Europe, via the HRS networks in Germany and the Baltic states. FCEV have now reached such a technological maturity that they are ready for commercialization. Market development rather than technology development is currently the main barrier for FCEV market introduction.

The main objective is to establish an interconnected HRS network to enable long distance travel between the capitals of the Nordic countries with a first fleet of FCEVs. The main objective can be broken down in the following underlying objectives:

1. Establish a chain of HRS along the Scandinavian – Mediterranean Corridor connecting the capitals Oslo, Stockholm, Helsinki and Copenhagen.
2. Secure dedicated renewable hydrogen production capacity to supply the demand of the FCEV fleet at the new HRSs.
3. Deploy a fleet of FCEV that raise the public awareness on hydrogen mobility and increase the visibility and acceptance of FCEV in Sweden.
In addition to the development in continental Europe, the Project will give a strong signal to car manufacturers that Europe has one interconnected extensive HRS network and is a primary market with a large unfulfilled demand for FCEVs.

Fig. 4. Nordic Hydrogen Corridor European Project – 8-10 new hydrogen refuelling stations (HRS). Black arrow=Existing/opening soon HRS. Green arrow=suggested locations for new HRS. Yellow circle=electrolyser

5. Hydrogen mobility in Poland

National implementation plans are in place in a number of countries, e.g. Belgium, France, the Netherlands, Sweden, etc. In Poland, the methodology developed “Circumstances of the national plan of hydrogenization of road transport” is of multi-stage character (HIT-2-Corridors European Project). Individual steps leading to the designation of the location of hydrogen refuelling stations in Poland (as the methodology alone seems to be of universal character) are as follows [11]:

- **Stage I**: Method allowing to identify regions in which the hydrogen refuelling stations should be located in the first place.
- **Stage II**: Method allowing to identify urban centres, in which should be located the said stations.
- **Stage III**: Method for determining the area of the station location.

In Table 1 is shown method allowing to identify regions (Stage I), urban centres (Stage II), area of the station location (Stage III).
Table 1. Method allowing to identify regions (stage I), urban centers (stage II), area of the station location (stage III) [11]

| Stage I                                      | Stage II                                      | Stage III                                                                 |
|----------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------|
| Average GDP per capita                        | Average distance of the cities, over 250 thousand inhabitants, from the place of hydrogen manufacture (acquisition) | Results of locating the stations in question obtained in stage I and II, and relying on the results of the measurement of average traffic volume of passenger cars on the roads leading to these cities or on selected road junctions located near these cities |
| Average population density (inhab./km²)      | Average distance of the cities, over 250 thousand inhabitants from the nearest hydrogen refuelling station located outside Poland |                                                                               |
| The number of people living in the largest cities in the region, out of the cities with > 250 thousand inhabitants | Number of taxes in the city | Traffic flow intensity of passenger cars was included on the roads leading to the following cities: Warsaw, Poznan, Krakow, Wroclaw, Katowice (Upper Silesia conurbation), Tri-City, Szczecin, Lodz, Bialystok |
| Average traffic volume of passenger cars on the national roads of international significance running through the region (passenger cars/24 hours) | Number of municipal transport buses |                                                                               |

Additionally, while pre-indicating subsequent hydrogen station locations taken into consideration were:
- average passenger car traffic intensity and average traffic volume projected for 2020,
- development of hydrogen filling stations network in the country,
- development of hydrogen refuelling stations in areas with potentially high demand for hydrogen fuel also by fleets of buses and taxis.

The order of investment: while taking into account the initial hydrogen refuelling stations locations (Stages I-III), in the first place included were:
- existing hydrogen refuelling capabilities in the neighbouring countries,
- the assumed future hydrogen refuelling stations locations in the Baltic Sea countries,
- new stations at the distances up to approx. 300 kilometers away from the existing stations or sequentially from the newly-opened stations.

With the above criteria, the order the construction of a hydrogen refuelling stations in Poland, in order of their creation, along the TEN-T corridors are: 1 - Poznan 2 - Warsaw, 3 - Bialystok, 4 - Szczecin, 5 - the Lodz region, 6 - the Tri-City region, 7 - Wroclaw, 8 - the Katowice region, 9 – Krakow (Fig.5).
Figure 5. Map of Poland with marked sites of the proposed public hydrogen refuelling station locations [11]

On the Fig. 6 shown the movement area of cars using fuel cells based on 9 hydrogen refueling stations situated on the national TEN-T road network by the 2030.

Figure 6. Penetration area of cars using fuel cells based on 9 hydrogen refuelling stations situated on the national TEN-T road network by the 2030 [11]: a) when driving in one direction (diameter of large circles – to approx. 600 km), b) when driving there and back (diameter of small, shaded circles - to approx. 300 km)

Full commercialization of hydrogen technology in Poland (the years 2040 – 2050): Respectively: 200 - 600 hydrogen refueling stations, Financial expenditures for the construction of hydrogen refueling infrastructure in the order of 155-190 million €. The assumptions: 600 thousand respectively - 2 million passenger cars, 500 - 1000 buses, 100 - 300 thousand cars transiting Poland annually.

6. Summary
Hydrogen as an automotive fuel is the lack of pollutants emission from motor vehicles’engines. The use of hydrogen fuel in the road transport to a large degree brings about independence from the import of crude oil and crude oil derived fuels. In the case of producing hydrogen by water electrolysis using electricity from renewable energy sources, the result is the use of "clean" energy (0,97 CO$_{2eqv.}$/1 kg H$_2$).
Hydrogen is characterized greater energy efficiency than fossil fuels, but smaller than in the case of EVs.

One of the most important ambitions of the governments of the Nordic countries is the transition towards fossil free road transport. 2 February 2017 the Swedish government adopted the so called Climate Law, which is a national agreement to cut transport emissions with 70% by 2030 from 2010 levels. To reach that level by 2030 a combination of suitable technological solutions is needed, in line with the AFID directive. A further roll-out of hydrogen infrastructure and FCEVs in Sweden is one of these solutions.

Via the German HRS network, the European project Nordic Hydrogen Corridor will connect the Nordic HRS network to the HRS networks in the rest of Europe along the TEN-T Scandinavian-Mediterranean core network corridor in Sweden during the period 2017 – 2020.

It is proposed, in the currently absence of the HRS stations in Poland and need to provide infrastructure for FCEV vehicles to build hydrogen refuelling base stations in years 2020 – 2030 (in order of their creation, along the TEN-T corridors) in: 1 - Poznan 2 - Warsaw, 3 - Bialystok, 4 - Szczecin, 5 - Lodz region, 6 - Tri-City area, 7 - Wroclaw, 8 - Katowice region, 9 - Krakow.

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