Hydrogenization of road transport in Poland, now and in the future

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Abstract. The advantages of hydrogen as an automotive fuel is the lack of pollutants emission from motor vehicles (with fuel cells) which is especially important in crowded city centers and with the possibilities of its local production. 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. As a result of verification, under Polish conditions, of the original method developed for determining the initial location of the hydrogen refueling station in Poland, in the pre-commercial phase (2020 - 2030), the said location has been indicated along TEN-T Corridors with the order of investment, taking into account above all the freedom to move around Poland of cars powered by hydrogen visiting Poland and transiting our country between other EU countries. Despite the strategic importance of developing hydrogen filling stations infrastructure, in the available materials, including various national programs for hydrogen propulsion technology developments, the explicitly formulated programming methodology for the development of these stations, has not been encountered. The methodology developed is of multi-stage character. 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:
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.

With the above criteria, the order the construction of a hydrogen refuelling stations in Poland:
1 – Poznan, 2 - Warsaw, 3 - Białystok, 4 - Szczecin, 5 - the Lodz region, 6 - the Tri-City region, 7 - Wroclaw, 8 - the Katowice region, 9 – Krakow.

1. Introduction
The world's first hydrogen refuelling station was opened in Dearborn in the USA. The following single hydrogen refuelling stations were activated usually on the occasion of major world events such as: EXPO in Osaka in 2005, in Zaragoza in 2007, in Shanghai in 2010, the Olympic Games in Beijing in 2008, etc.

The dynamic development of the number of hydrogen refuelling stations occurred at the beginning of the second decade of the twenty-first century. For example, in 2012 there were 27 new hydrogen refuelling stations opened in the world, in 2014 17 stations. In July, 2014 the Linde Company began
mass production of hydrogen refuelling stations (28 already ordered by Japan). Launching of the new hydrogen refuelling stations was accompanied by the closure or temporary suspension of the operation of some stations already opened - mostly in the United States (20 stations), but also, for example in Italy (16 stations), or Spain (3 stations). In March 2015 there were 184 hydrogen refuelling stations operating in the world (82 in Europe, 63 in North America) [1,3,5,9].

Practical use of hydrogen as a fuel carrier is transport, including in particular road transport. In recent years 2 motor companies (Hyundai, Toyota) have launched the serial production of fuel cell vehicles (hereinafter referred to also as hydrogen-fuelled or hydrogen vehicles) and others such as Volkswagen, Mercedes Benz, BMW, General Motors also produce such vehicles. The start of serial production by those companies depends on the availability of expanded hydrogen refuelling network of HRS (Hydrogen Refueling Stations). In 2016 there were only c.a. 200 such stations available in the world. It is expected that by 2020 the number of HRS should come to approx. 1000 and by 2025 – to c.a. 3500 (table 1).

| Year | USA | Europe | Asia | Total |
|------|-----|--------|------|-------|
| 2016 | 60  | 100    | 103  | 263   |
| 2020 | 130 | 520    | 340  | 990   |
| 2025 | 600 | 2000   | 830  | 3430  |

This HRS in 2025 should provide service for approx. 2 million hydrogen vehicles.

Currently approx. 3 thousand vehicles fuelled with hydrogen are used in the world, including more than 1000 in the US and Japan and several hundred in Western Europe. A dynamic growth of fleets of hydrogen vehicles is planned – for example China expects to have 50 thousand hydrogen vehicles in 2025, to eventually exceed one million in 2030, whereas Japan will have a fleet of 200 thousand hydrogen vehicles in 2025 and approx. 800 thousand in 2030. According to projections of 2014 – the European fleet of hydrogen vehicles is expected to have 350 thousand vehicles in 2020, the fleet in Japan – 100 thousand, in Korea – 50 thousand and in the US – 20 thousand [11].

Also, the fleet of hydrogen-fuelled buses is to be developed – in Europe it will have 1000 buses in 2020, while for instance in South Korea – almost 30 thousand buses by 2030. Also, other means of transport fuelled with hydrogen are developed, e.g. vessels, trams and railway engines (in 2017 the first hydrogen railway is to start in Germany) and even airplanes (German four-seat HY4 airplane tested in 2016).

2. Ecological aspects of implementing hydrogen fuel

The reason to stimulate research on the development of technology that uses alternative sources of energy in the road transport is, on the one hand a political issue resulting from the security of the oil acquisition and on the other hand, the question of the assumptions (also of a political nature) aimed at limiting in absolute terms, or at least limiting the growth of the pollutants emissions from internal combustion engines, including the reduction of greenhouse gases emission [9].

The ecological concerns include premise for transport policy in the EU. According to the transport strategy of the European Commission (EC White Paper of 2011) by the 2050 the vehicles powered by combustion engines are to disappear from the European cities. By the 2030, by a half is to be reduced the number of cars with internal combustion engines operating in the cities. Public transport relying on electric, hybrid and hydrogen vehicles is to, among the others, take over the majority of passenger transport. This European Commission's strategy is to affect the reduction in fossil fuel consumption and improving the air quality, especially in cities [9].
Regardless of the realistic evaluation of conclusions from the White Paper from the point of view of the Polish economy, the European Commission and some Member States will aim to accept the targets of significant reduction in pollutants emissions from transport. One of the promising alternatives seems to be a market for electric vehicles, including cars equipped with fuel cells that require hydrogen supply.

Hydrogen fuel used in the future, primarily in the fuel cells used to generate electricity that powers the electric motors of vehicles, is one of the alternative routes leading to the achievement of the objectives formulated in the European Commission’s White Paper.

Hydrogen production as the result of the water electrolysis or e.g. methane reforming, is the best possible action from the point of view of protecting the natural environment against the destructive effects of transport, including the motorism. However, the basic condition that must be met in order the hydrogen could replace energy sources traditionally used in road transport is to develop economic, efficient and rapid method of hydrogen production based on energy from renewable sources. Currently, 48% of the produced hydrogen is obtained through reforming of methane using steam, 30% from crude oil (mainly in refineries), 18% from carbon, and the remaining 4% from the water electrolysis [12].

To fully understand emission when hydrogen is used for fuelling vehicles, it is necessary to analyse the life cycle of that fuel (greenhouse gas emissions for every energy carrier used for its production).

In hydrogen production there are significant differences in environmental impact, depending on the method of its production. Three main options that seem most likely at present result in different emission of greenhouse gases, i.e. in the cycle of hydrogen production (table 2) [10].

| Origin                                | kg CO$_2$-equiv/kg H$_2$ |
|---------------------------------------|--------------------------|
| Natural gas (reforming)               | 11.9                     |
| Biomass (gasification)                | 4.8                      |
| Electricity (electrolysis; with the use of wind energy) | 0.97                     |

There is a great variety in the use of raw materials as – for example – gasification based on biomass of lower carbon content results in reduced estimated overall emission of CO$_2$. The aforesaid emission is conservative, considering for instance the emission of methane.

In electrolysis according to the above example – over 75% of the said emission is generated by production and assembly of wind turbines. During electrolysis the origin of electrical energy is of key importance for the levels of emissions.

Table 3 below regarding emission of greenhouse gases in the use of various fuels shows average emission levels for biogas and E85 fuel [10].
Table 3. Emission of greenhouse gases in the use of various fuels [12].

| Type and origin of a fuel                              | Direct emissions by vehicles [kg CO₂ eqv/100 km] | Total gross emission together with emissions from fuel production |
|-------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------------------|
| Vehicle using biogas                                  | <8.4                                             | 8.4                                                             |
| Vehicle with a self-ignition engine¹ effective in terms of fuel consumption¹ | 9.8                                              | >9.8                                                            |
| Vehicle fuelled with E85                              | 5.0                                              | Depends on the origin of ethanol                                  |
| Average emission for new vehicles in Sweden in 2012   | 13.5                                             | >13.5                                                           |
| EU emission target for new vehicles w 2020 r. [12]    | 9.5                                              | >9.5                                                            |
| Vehicle with fuel cell, hydrogen from natural gas [7] | 0                                                | 11.9                                                            |
| Vehicle using fuel cell, hydrogen from biomass [8]    | 0                                                | 4.8                                                             |
| Vehicle using fuel cell, wind power [9]               | 0                                                | 0.9*                                                            |

* including 0.7 from wind turbine production
¹ average for vehicles of several producers

Other harmful emissions (NOₓ, SOₓ, PM) had been reduced significantly since 1990 for all vehicles, including also petrol and diesel-fuelled vehicles. However, emission limits of combustion pollutants are still exceeded in real traffic conditions, especially in urban areas. Those emissions generate additional external costs due to health impairment, damages to buildings, etc. and occur in result of all types of combustion in engines of vehicles, except for fully electrical vehicles (BEV) or fuel cell vehicles (FCEV) [10].

Significant ecological effects of implementing hydrogen fuel are expected for example in France. In 2030 the projected fleet of about 800 thousand hydrogen vehicles – assuming average annual mileage of a statistical car of 16 thousand km and production of 75% of hydrogen used by transport, with the use of electrolyzers located in HRS, should ensure reduction of CO₂ emission of 1.2 Mt (a volume corresponding to emission generated by 780 thousand diesel-fuelled vehicles) and in 2050 – even up to 10.4 Mt [5].

The use hydrogen vehicles in 2030 should help reduce – apart from CO₂ emission – also the emission of NOₓ, SO₂ and PM in total mass of 1300 tons, which would bring roughly EUR 100 million savings in terms of external costs.

The annual overall external costs including – apart from costs of harmful emissions also costs of noise – would be reduced in 2030 from EUR 510 /car with a traditional diesel engine to EUR 160/ hydrogen-fuelled car, which – assuming the development of a fleet of hydrogen vehicles – would
produce savings of approx. EUR 140 million annually in external costs and in the period 2015 – 2030 of EUR 500 million annually [5].

In physical terms the costs of CO₂ emission in result of the development of a fleet of hydrogen vehicles should come to 1% of the global emission of CO₂ generated by a fleet of light vehicles in 2030, 5% of emission in 2040 and 9% of emission in 2050.

It should be emphasised that hydrogen is the fuel that will never run out as 94% of the matter in the Universe is hydrogen. Moreover, it has a high calorific value (lower) when compared with other fuels (about 120 MJ/kg). It also has drawbacks, such as, storage problems, the absence of a free state or very broad combustibility limits.

3. Circumstances for the vehicle transport hydrogenization national plan in Poland

An essential element and direction for the development of road transport based on hydrogen-powered fuel cells is to create an alternative hydrogen refuelling infrastructure. This type of infrastructure in Poland does not currently exist.

Polish law on electromobility and alternative fuels talks about the possibility of determining the location of hydrogen refuelling points (HRS) for the needs of vehicles with fuel cell (FCEV). The location of such points must be justified by the needs of the development of the alternative fuel market [8]. This law implements the directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels infrastructure [3].

The costs of hydrogen refueling infrastructure are less than often thought. Roadmap of Hydrogen Council shows that building the required refueling infrastructure would cost $1,500 to 2,000 per FCEV until 2030. This is in the same order of magnitude as the cost for the recharging infrastructure for BEV, as a home charger currently costs around $2000. [7]. By 2030, costs of refueling infrastructure could decrease to less than $1000 per FCEV. A study comparing infrastructure costs for 20 million FCEVs and 20 million BEVs in Germany found that, when required grid investments are considered, that total cost per FCEV may even be lower than for BEVs [4].

Despite the strategic importance of developing HRS network, the explicitly formulated programming methodology for the development of these stations, has not been encountered.

The methodology developed is of multi-stage character. Individual steps leading to the designation of the location of HRS in Poland (as the methodology alone seems to be of universal character) are as follows:

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.

Stage IV: Method used to indicate a specific location of hydrogen refuelling station.

Stage V: Method indicating the preferred order of building investments in creating future network of hydrogen filling stations on the Polish territory.

In any of the said stages the group of 3-5 basic characteristics was adopted that determine, according to the experts, the potential future demand for hydrogen fuel, whose likely impact strength was determined by giving them the appropriate rank on a scale of 1 to 5 [9]. Detailed assumptions, acting procedures, numerical information, etc. contained by the task No. 5 entitled "The selection criteria for the location of HRS on the Polish TEN-T network" [9].

According to the guidelines of the HIT-2-Corridors project, as the indications of development of the network of HRS on the territory Polish, was the assumption taking into account firstly the possibility of refuelling with hydrogen connecting the areas between the Polish western border and the Baltic countries and next e.g. via ferry - with Finland. This idea is adhered to by enabling the safe use of hydrogen cars by their owners crossing the northern border of Poland (via ferry). This would provide, in the first place, opportunity for maintaining continuity of the passage of hydrogen cars along the transport corridors in these international directions within the EU.
Pointing to the proposed order of investments in the construction of HRS in Poland and taking into account the above-mentioned reasons, the preliminary aspect of locations in the cities or urban areas selected according to the rankings stages I to III, was considered.

In the first place taken into account were:

- already existing refuelling opportunities in the neighbouring countries,
- the expected future HRS locations in the Baltic countries,
- gradually increasing the area available for hydrogen-powered cars as a result of the subsequent location of new stations at distances up to 300 km from the existing or sequentially from the newly-opened ones.
- in addition, while pre-indicating another HRS locations, taken into account were:
  - a size of average passenger car traffic intensity along the selected national roads according to available data, the average traffic volume projected for 2020,
  - development of HRS network ensuring gradually increasing the area of accessibility of other Polish regions by hydrogen cars,
  - development of HRS in areas with potentially high demand for hydrogen fuel also by the fleet of city buses and taxis.

With the above criteria, the order of preliminary proposals to build HRS in Poland are as follows: 1 - Poznan 2 - Warsaw, 3 - Białystok, 4 - Szczecin, 5 – Lodz area, 6 - Tri-City area, 7 - Wroclaw, 8 - Katowice region, 9 - Krakow (figure 1).

**Figure 1.** The movement area of cars using fuel cells based on 9 hydrogen refuelling stations situated on the national TEN-T road network by the 2030 [4], when driving in one direction (large circles - to approx. 600 km), and when driving there and back (small circles - to approx. 300 km).

Factors contributing to a possible interest in the development of hydrogen technology in the road transport in Poland:

- The current and planned dynamic development of hydrogen refuelling infrastructure in the Poland’s neighbouring countries (Germany, Baltic Sea region countries).
- The legitimacy of the development of hydrogen refuelling infrastructure in Poland to ensure the continuity of movement of hydrogen cars across the EU, firstly along the TEN-T network.

Factors boosting the development of hydrogen technology in the transport:
Due to the innovativeness of the introduction of hydrogen technology in transport, it should be expected that economic effectiveness of the actions taken will only be evident in the full commercialization phase of the technology.

The pre-commercial phase of the development of hydrogen technology will require the use of various instruments enabling the implementation of the assumed political strategy. They should be varied instruments of economic and administrative nature, addressed both to the users of electric vehicles with fuel cells, and the users of vehicles with conventional engines.

The implementation and spread of hydrogen technology in the Polish transport requires proper lobbying, including the development of a multi-stage information - education program.

HRS stations must be supplied with hydrogen. It is reasonable for the supply of hydrogen to be produced at or near the station's location. Hydrogen transport with existing pipelines is the lowest cost option. The transport of compressed hydrogen gas by road is costly, especially a distance of over 300 km. The transport of liquid hydrogen over long distances is more economical (higher mass of hydrogen) than compressed in pressure tanks. The basic challenge for supplying hydrogen is to reduce delivery costs.

4. Summary
It seems that presently the practical development of the hydrogen technology is in a ground-breaking phase. The fact that many international programs are dedicated to the expansion of the HRS network and gradual enlargement of the fleet of hydrogen vehicles, especially with many such initiatives launched by the public administration a number of countries, may help overcome the deadlock.

It may be possible to overcome the impasse also owing to the fact that costs of building HRS, hydrogen vehicles and hydrogen itself are gradually decreasing.

The cost of constructing one HRS which already dropped from EUR 1.5 million to approx. EUR 1 million, are expected to decrease to EUR 400 – 470 thousand in 2030 [2].

The costs of production of hydrogen-fuelled passenger cars should decrease from EUR 62 thousand in 2015 to EUR 25 thousand in 2020, and finally up to EUR 18 thousand in 2050 [9]. Also the unit price of hydrogen and the annual service costs of a hydrogen vehicle are expected to decrease [2].

Maintaining in many countries the financial and non-financial support systems, purchase and use of low-emission and emission-free vehicles combined with reduced costs of the hydrogen fuel technology ought to bring the start of a real, commercial use of the said technology.

Poland should in the coming years to create a network of base HRS thereby allowing the transit of hydrogen cars.

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