A comparison of distribution of energy between Fuel Cell Electrical Vehicles and Battery Electrical Vehicles in Europe

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Abstract

In the current framework of prohibition of motor vehicles using fossil fuels (diesel and gasoline) taken by several mains cities in Europe, the question arises of the development of the infrastructure of distribution of alternative energies, namely hydrogen (with Fuel Cell Electrical vehicles) and electricity (with Battery Electrical Vehicles). We first compare the main advantages/constraints of the two alternative propulsion modes for the user. Then we review the existing studies on the deployment of new hydrogen distribution networks and compare the deployment costs between the hydrogen and electricity distribution networks for Germany. Finally, we give some ideas for future studies on the subject.

Keywords: Hydrogen distribution infrastructure: pipelines, Hydrogen distribution Economics: cost comparison with Electrical Vehicules.

1. Introduction

Since the diesel scandal (See the report of Transport and Environment [12]), public authorities of several main Europeans cities have decided to progressively eliminate diesel and gasoline cars from the city centers. For example, the municipality of Paris has the objective to eliminate diesel cars in 2024 and gasoline cars in 2030. Recently, region of Brussels announced her objective to eliminate diesel vehicles from the capital of Europe in 2030. In the UK, as indicated by the Institution of Mechanical Engineers [7], the Government announced a ban on the sale of new passenger vehicles with conventional diesel and gasoline engines by 2040. These two modes, as emphasized by Shukla et al [10] are known to cause high levels of air pollution and are blamed for contributing to climate change and global warming.

In this context, two alternative propulsion modes can be considered (See Shukla et al [10]):

- electric cars using compressed hydrogen for powering a Fuel Cell vehicle (named FCEV for **Fuel Cel Electrical Vehicles**);
- electric cars using electricity with a Battery (named BEV for **Battery Electrical Vehicles**).

As indicated by Shukla et al [10], since these vehicles have a limited range, a convenient access to refueling facilities is an important factor for the large scale adoption of these two modes. In other words, a lack of refueling stations will constitutes a major obstacle for the large scale adoption of these new vehicles. And as the construction of new refueling infrastructures (for FCEV and for BEV) is capital intensive consuming, it is important to study their respective development costs.

We first summarize (See Section 2) the *advantages* and *constraints* of the two alternative propulsion modes concerning the following criteria:

- the autonomy of the vehicle;
- the refueling time;
- the using cost;
- the purchasing cost;
- the carbon emissions.

In Section 3, we present a review of the main studies for the deployment of new hydrogen transmission infrastructures for several european countries. Then we present in Section 4 the main ideas of the a comparison of the costs of the new distribution infrastructures made by Julich Institute [9] for Germany where most of the electricity surplus comes from green energy (solar cell, wind). In Section 5, we give ideas for new research directions on this subject of comparison of the cost of the two alternative modes and finally in Section 6, we give the main conclusions.

2. Advantages/constraints of the two car propulsion modes

Lets begin by presenting two existing models on the european market as an illustration of the advantages/constraints of the two alternative propulsion modes (See Table 1 for a presentation of other existing models):

- Concerning the **BEV**, the Nissan Leaf is offered on the european market at a price of 32.640 €, including taxes. The manufacturer announces an autonomy of 250 km in standard cycle, an autonomy in real situation of 140 km. A complete charging time on a socket at home takes 13 hours. It is also possible to reload up tu 80% of the nominal capacity on a fast chargor in 30 minutes.

- Concerning the **FCEV**, the Toyota Mirail is offered on the european market at a price of 79.200 €, including taxes. The manufacturer announces an autonomy of 500 km. A complete charging time takes 3 minutes.

Clearly, the advantages (See CNRS [5]) of hydrogen cars are, on one side, the *time of reloading* (3 minutes) and the *autonomy of the car* (up to 600 km), against hours for loading a BEV at home and a lower autonomy in real traffic conditions. Refueling time and autonomy are thus similar to a classical diesel vehicle for FCEV.

The major obstacle (See CNRS [5]) of hydrogen cars is clearly *the cost*: 79 200 € for the Toyota Mirail, when French people spend on average 25 000 € for a new car. An other major disadvantage is the *very reduced number of hydrogen refueling stations*: there are currently only 22 hydrogen refueling stations throughout France (See AFHYPAC [3]) and 40 in Germany.

An other problem is that hydrogen is *currently produced from fossil fuels such as gas*, a method of production that is not renewable. As indicated by Singh et al [11], hydrogen can be produced by several modes:

- The *steam methane reforming* (SMR) where natural gas reacts with steam to produce *hydrogen* and *carbon dioxide.* As indicated by Singh et al [11], about half of the global supply of hydrogen in 2015 was produced by reforming of natural gas (48 %). This mode is not suitable for the development of an hydrogen economy for two reasons: reforming of natural gas produces as much pollution and CO_2 as burning the natural gas directly; and if this mode is used when the economy of hydrogen will be fully developped, the increase of the demand of natural gas to

Model	Type	Price	Autonomy	Charging time
BMW I3	BEV	32.100 €	200 km	8 hours
Citroen C-Zero	BEV	30.235 €	150 km	15 hours
Hyundai Ioniq	BEV	35.850 €	280 km	7 hours
Kia Soul EV	BEV	35.400 €	200 km	8 hours
Nissan Leaf	BEV	32.640 €	140-250 km	13 hours
Peugeot Ion	BEV	30.370 €	150 km	11 hours
Renault Zoe	BEV	25.900 €	200-350 km	10 hours
Tesla S	BEV	75.700 €	600 km	38 hours
Volkwagen E-Goff	BEV	39.350 €	300km	17 hours
Mean	**BEV**	**37.505 €**	**261 km**	**13 hours**
Toyota Mirail	FCEV	79.200 €	500 km	3 minutes
Honda Clarity	FCEV	57.600 €	650 km	3 minutes
Hyundai ix 35	FCEV	66.550 €	500 km	3 minutes
Mean	**FCEV**	**62.075 €**	**575 km**	**3 minutes**

Table 1: Existing models on european market

produce hydrogen would deplete the natural gas reserves. Currently *steam methane reforming* (SMR) is the cheapest method for hydrogen production.

- The *partial oxidation of oil* (POX) is the process were the hydrocarbons is submitted to partial oxidation at a temperature of 1300 - 1550. This oil gasification process is currently the second most used mode to produce the hydrogen.

- The *coal gasification* (CG) is the process where the coal is submitted to a partial oxidation at a temperature of 1200-1350 yielding a mix of *carbon monoxyde* and *hydrogen*. This gasification process is currently the second most used mode to produce the hydrogen (30%). This coal gasification process is currently the third most used mode to produce the hydrogen (18 %).

- The *electrolysis of water* is the process by which water molecules are split into *hydrogen* and *oxygen* using an electrolyser device. Electrolysis is preferred in the industry if high purity hydrogen is needed but is more expansive. The great advantage of this production mode, as indicated by Singh et al [11], is the fact that hydrogen can be produced by the electrolysis of water from *electricity produced by solar photovoltaic (PV), wind power, hydropower* and thus the electrolysis only produces *pure oxygen* and *pure hydrogen.* The electrolysis accounts for 4% of the current production of hydrogen.

The two major disadvantages of BEV vehicles are the *real autonomy* (no more than 260 km in real traffic conditions for the main existing vehicles) and the *long time to charge the battery* at home (13 hours as mean time). The major advantages are the *lower cost* of the vehicle and the *large accessibility of the electrical network* to charge the vehicles.

Concerning the social and environmental disadvantages of BEV vehicles, the Institution of Mechanical Engineers [7] cites the two following. First, the most commonly used battery is the lithium-ion battery. However, the required increases of materials needed for the production of batteries lead to environmental and human suffering. Another disadvantage concerns the aspect of the life of the lithium-ion battery: only 5% of lithium-ion battery are currentlly recycled.

Concerning the CO_2 emissions, the comparison depends on the production mode for electricity and for hydrogen. Since the electricity mix is different from country to country in Europe, a comparison can only by made within a country. For example, for Germany, Robinius et al [9] consider a high use of renewable surplus electricity for the production of hydrogen and compute 2,7 gr of CO_2 per kilometer. They consider the direct use of the electricity grid to recharge BEV and compute 20,9 gr of CO_2 per kilometer (See Table 2).

Model	CO_2 per km
BEV	2,7 gr
FCEV	20,9 gr

Table 2: CO_2 emissions in Germany

As indicated by Shukla et al [10], one of the hydrogen's primary advantages is that its only oxydation product is water vapor. In other words, it produces no carbon dioxyde if it is produced by electolysis of the water and if the electricity is produced by wind or solar cells.

Note also, as mentioned by Institution of Mechanical Engineers [7], that the hydrogen constitutes a potential solution for heavy goods vehicles, aircraft and shipping, all the forms of transport that are currently increasing their oil use. Note that hydrogen fuel cells busses are already used in Aberdeen, London (UK) and Dunkerque (France). As mentioned by Institution of Mechanical Engineers [7]), these busses have an advantage of producing zero GHG emissions and zero NOx emissions. As demonstrated above for personal cars, theses busses have also a significantly better range than their electric equivalents.

3. Studies on the deployment of hydrogen distribution networks

Many countries in Europe are expecting that hydrogen will constitute a part of the solution to achieve the European goal of reduction of CO_2 emissions in the next decade. As emphasized by Shukla et al [10], the development of an appropriate infrastructure for a convenient access to refueling stations is a condition of a large deployment of this new propulsion mode for private vehicles. Shukla et al [10] suggest to invest in these new refueling structures in areas which result in maximum impact.

3.1. Prevision for the deployment of hydrogen infrastructure in Norway

One of the first studies on the subject was done in 2010 by Stiller et al [4]. The Norway project aims to model the hydrogen infrastructure to provide a decision support for introducing hydrogen in the Norwegian energy system. As emphasized by Stiller et al [4], Norway, with a large part of production of electricity by hydropower and an high potentiel of windpower, is an ideal country to introduce renewable hydrogen production. Also, with an extremely high level of taxation on new vehicles, Norway can use tax exemption to support the introduction of hydrogen vehicles on the market.

The study considers a progressive penetration of hydrogen cars on the Norwegian market to end in 2050 with a market share of 70%. The model considers that the regional use of hydrogen in Norway will be initiated in population centers such as Olso, Stavanger, Grenland, Bergen and Trondheim. They also consider additional fueling stations along corridors linking the equipped regions. Then the model considers that the hydrogen use will be progressively generalized to the rest of the country. The model considers an expansion of the number of refueling stations from 46 in 2020 to 1.100 in 2050.

The main results of the study are the following:

- The *decentralized production*, especially electrolysis, will play a central role due to the sparcity of the population in Norway. This shift toward *onsite electrolysis* is also obtained by considering a *high CO_2 taxation of 100 €/t CO_2*.
- The *cost of hydrogen* will be competitive with other propulsion modes from a penetration rate of 5% anticipated for 2025.
- Since a penetration of 25%, the transport by gaseous hydrogen trucks is replaced by pipelines.

3.2. Deployment of large-scale hydrogen infrastructure for the transport sector in the Netherlands

In 2011, Konda et al [8] consider a multi-period optimisation model to design the spatial deployment and the time deployment of large-scale hydrogen infrastructure for the transport sector in the Netherlands.

The H_2 demand is spatially estimated using the regional population, the car density and the average daily distance travelled. Concerning the supply side, Konda et al [8] consider four production modes: *Steam methane reforming*, *Coal gasification*, *Biomass gasification* and *Water electrolysis*. Since the authors consider that most of the hydrogen will be produced from hydrocarbon ressources (natural gas, coals and biomass), they consider also *carbon capture and storage) to achieved the european goal of CO_2 emissions reduction.*

For the transport of hydrogen, the authors consider the two phases: compressed H_2 *and* liquefied H_2. As emphasized by the authors, liquefaction is an energy intensive process but is cheaper to transport due to its high energy density. Trucks are used for transporting the liquid hydrogen or the compressed gaseous hydrogen. In the Dutch case, they don't consider the use of pipelines to transport the hydrogen. The transportation capital costs include tube trailer buying costs (for liquid hydrogen) and the tanker buying costs (for gaseous form). The transportation operating costs include labor costs, fuel costs, maintenance costs and general costs.

The main results of the study are the following:

- The Dutch case study reveals that the transition to a large-scale H_2 based transport is economically feasible for the three penetration scenarios for HFCV in the Netherlands in 2050 (pessimistic with 12% of market share, base case with 25% and optimistic case with 50%).
- The attainable CO_2 reduction potentiel is limited to 30% due to the used of hydrocarbon ressources (natural gas, coals and biomass). With the use of carbon capture and storage, 85% of gas emissions can be avoided.
- It is observed that the Rotterdam area plays a major role and that the H_2 supply network ressembles the current Dutch gasoline network.

Note that, contrarelly to the Norwegian case where the population is sparse, the Netherlands is a small and densely populated country.

3.3. Optimal design and time deployment of a new hydrogen transmission network for France

In 2013, André et al [1] consider the problem of the determination of the optimal structure for the distribution of hydrogen to refueling stations in France. For the specific case of hydrogen, pipeline networks compete with other hydrogen carriers: compressed gas trucks and liquid cryogenic trucks.

They define a local search method that simultaneously looks for the *least cost topology of the network* and for the *optimal diameter of each pipe*. These two problems were generally solved separately these last years. The application to the case of development of a new hydrogen pipeline networks in France has been conducted.

Concerning the demand in France, they consider the current urban areas with more than 100,000 inhabitants (78 as in year 2000). The demand for hydrogen has been estimated based on a full conversion of the car engines from gasoline to hydrogen for a horizon beyond 2050.

The main conclusions of this study are the following:

- The *two stage approach generally used* (which first looks for a topology of minimal length and then optimizes the diameters) is *not the best one*: *increasing the length of the network can help to decrease the network cost by using smaller diameters.*

- The network layout follows some *natural corridors* (Rhone's valley, Paris-Bordeaux, French riviera, ...) and looks like the *natural gas network.*

- The *investment costs in the network are reduced by 18% with respect to the minimal spanning tree* (from 2.868 to 2.347 billions €) by reducing the *average diameter* by 30 % (from 440 mm to 300 mm) and by increasing the *total length* by 5 % (from 5,035 km to 5,274 km).

In 2014, André et al [2] consider the problem of the *time deployment of the new network for France.* Concerning the *time evolution of the hydrogen demand*, they consider two *hydrogen penetration scenarios* on the market of cars taken from HyFrance (See [6]):

- a *high scenario* hydrogen market share for fuels for individual cars ending with 74,5% share of the market;

- a *low scenario* for the hydrogen market share ending with 20% share of the market.

As shown in Table 3, the *percentage of cars fueled with hydrogen* and the *year* variables are explicitly linked for each demand scenario.

This study shows that:

%	2010	2015	2020	2025	2030	2035	2040	2045	2050
H	0.1	1.5	3.3	10	23.7	35	55	68	74.5
L	0.05	0.05	0.1	1	2	5	10	15	20

Table 3: Two scenarios for the hydrogen penetration on the market of individual cars

- for the mid term perspective (before 2025) and low market share (lower than 10%), the *trucks are the most economical options* to deliver the hydrogen to the refueling stations.
- for the long term, the *pipeline option is considered as an economically viable option as soon as the hydrogen energy market share for the car fueling market reaches 10%.*

Note also that the authors consider a centralized hydrogen production plant in this study.

4. A comparison of the costs of new distribution infrastructures

In 2017, Robinius et al [9] consider the problem of the design of the new infrastructure required for supplying battery and fuel cell electric vehicles in Germany. They consider a wide variation of the demand for these new electric cars: from one hundred thousand to several million electric vehicles with hydrogen or electricity. They consider that both technologies will take advantage of the unavoidable surplus electricity coming from renewable plants (wind and solar) that will dominate the German energy systems in the near future.

They perform an extensive meta-analysis of existing studies on infrastructure. For a high market penetration, they consider that existing studies failed to be extended and they developped a new analysis to define the design of new transmission infrastructures.

The main results of this study are the following:

- They demonstrate that, for low market penetration levels of a few hundred thousand vehicles, the costs of the two infrastructures (hydrogen refueling stations and battery charging networks) are essentially the same.

- Hydrogen is then more expensive during the transition period to electricity-based generation via electrolysis and geological storage, both of which are needed to access renewable hydrogen from surplus electricity.

- If vehicle penetration increases up to 20 million vehicles, a battery charging infrastructure would cost around €51 billion, making it more expensive than hydrogen infrastructure, which comes in at around €40 billion.

5. Future research

Since the electricity mix is very different for France and Germany with many nuclear plants at a lower penetration of renewable electricity (produced by solar cells and wind), the same analysis that was made for Germany by Robinus et al [9] must be done to compute:

- The CO_2 emissions per kilometer for the two alternative propulsion modes : BEV and FCEV;

- The total cost of the two alternative distribution infrastructures.

Note that the cost of the hydrogen transmission infrastructure was already computed in 2014 for France by André et al [2]. This study should be completed to include the cost of the deployment of the refueling stations.

More generally, the production cost of the hydrogen and of the electricity must also be included in the research to *compare the total cost* (production, transport and distribution) for the two propulsion modes.

6. Conclusions

In the near future, electric charging and hydrogen fueling will constitute *practical solutions to reduce the polluting gas emissions from transportation activities*. As indicated by Singh et al [11], the transport sector is a major contributor to the global $\mathrm{CO_2}$ emissions and is a sector where the use of fossil fuel increases. For example, hydrogen powered vehicles (FCEV) have zero emissions (at the use and at the production if the electricity comes from renewable sources).

Another important advantage of the two modes is the *use of renewable energy resources*, BEV when charging during the night where the demand for electricity is lower and hydrogen using the surplus of renewable electricity (solar photovoltaic, wind power, hydropower) that can be store in gaseous form.

In fact, as mentioned by the Institution for Mechanical Engineers for UK [7], the hydrogen can be used to absorb surplus of renewable electricity using the gas grid to store this surplus. Power to Gas is the straightforward solution when there is a surplus of renewable electricity on the National Grid in the case of high level of production of wind turbines or solar cells, or in the case of lower demand. As mentioned by the Institution for Mechanical Engineers [7], the excess power can by used to produce hydrogen through water electrolysis. This ensures that no renewably produced electricity is wasted by using the existing natural gas network to store the surplus of hydrogen produce by electrolysis.

A complementary combination of the electric charging and the hydrogen refueling infrastructure will thus give a key to a more sustainable transportation system: the BEV will be used for short distance travel and hydrogen cars will meet the requirement in long distance and heavy duty transport by using fuel cell electric vehicles.

For Germany, the comparison of the cost of the two alternatives (BEV and FCEV) was done with the following result: for low market penetration levels of a few hundred thousand vehicles, the costs of infrastructure are essentially the same. Hydrogen is then more expensive during the transition period to electricity-based generation via electrolysis and geological storage, both of which are needed to access renewable hydrogen from surplus electricity. If vehicle penetration increases up to 20 million vehicles, a battery charging infrastructure would cost more than the hydrogen infrastructure.

The results of this study are depending on the electricity mix. The study should be extended for another important European country with a different electricity mix, namely France with many nuclear plants. The study should also be completed to include the total cost (production cost, transportation cost and distribution costs) for the two propulsion modes.

References

[1] Jean André, Stéphane Auray, Jean Brac, Daniel De Wolf, Guy Maisonnier, Mohamed-Mahmoud Ould-Sidi, Antoine Simonnet, Design and dimensioning of hydrogen transmission pipeline networks, *European Jour-*

nal of Operational Research, Volume 229, Issue 1, 16 August 2013, Pages 239-251.

[2] Jean André, Stéphane Auray, Daniel De Wolf, Mohamed Ould Sidi, Antoine Simonnet, Time development of new hydrogen transmission pipeline networks for France, *International Journal of Hydrogen Energy* Volume 39, Issue 20, 3 July 2014, pp 10323-10337.

[3] Association Franaise pour l'Hydrogne et les piles combustibles, mobilit hydrogne en France, May 2018, http://www.afhypac.org/mobilite-hydrogene-france/

[4] Christoph Stiller, Ulrich Bnger, Stfen Moller-Holst, Ann Mari Svensson, Karin A. Espegren, Matthias Nowak, Pathways to a hydrogen fuel insfratstucture in Norway, *International Journal of Hydrogen Energy* 35, 2010, pp 2597-2601.

[5] CNRS, Hydrogen Car for all ?, *European Fuel Cell Car Workshop 2017*, Orléans, France, March 1-3, https://news.cnrs.fr/articles/hydrogen-cars-for-all

[6] HyFrance 2 project. Final Report: Evaluation technico- Economique du développement dune filière hydrogène en France et de ses impacts sur le système énergétique, léconomie et lenvironnement http://www.ecolo.org/ documents/documentsinfrench/H2-rapport-HyFrance07.pdf; 2007.

[7] Institution of Mechanical Engineers, Energy from Gas: Taking a Whole System Approach, London, May 2018.

[8] Murthy Konda, Nilay Shah and Nigel Brandon, Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: the case for the Netherlands, *International journal of hydrogen energy* 36, 2011, pp. 4619-4635.

[9] Martin Robinius, Jochen Linen, Thomas Grube, Markus Reu, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten, Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles Schriften des Forschungszentrums Julich, Reihe Energie & Umwelt / Energy & Environment Band / Volume 408.

[10] Aviral Shukla, Joseph Pekny, Venkat Venkatasubramanian, An optimization framework for cost effective design of refueling station infrastructure for alternative fuel vehicles, Computers and Chemical Engineering 35, 2011, pp 1431 1438.

[11] Sonal Singh a, Shikha Jain a, Venkateswaran PS a, Avanish K. Tiwari a,1, Mansa R. Nouni b, Jitendra K. Pandey a, Sanket Goel, Hydrogen: A sustainable fuel for future of the transport sector, Renewable and Sustainable Energy Reviews 51 (2015) 623633, July 2015.

[12] Transport et Environnement, Don't Breathe Here: Tackling air pollution from vehicles, final report, 55 pages, 2015.