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Comparison between Electricity and Hydrogen as CO_2-Free Secondary Energy Carriers

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Executive Summary

As future CO_2 -free final energy carriers, electricity and hydrogen have recently been in the focus of often polarising discussions. This study compares the two above-mentioned energy carriers. Based on a comprehensive analysis of well-to-wheel process chains, it turns out, that in the short- and medium term, the application of electricity in vehicles with battery drive reveals considerable advantages over vehicles with hydrogen drive when comparing energy efficiency, greenhouse gas emissions and total cost of ownership. The fact that until today the cruising range of battery-electric vehicles is still quite low and at the same time their charging time is quite long makes these vehicles in some cases less comfortable or applicable - especially for long distance driving. However, small town cars and certain user groups (especially commuters) are even today not adversely affected by low cruising ranges of these vehicles. In view of further progress in battery development, Plug-in Hybrid Electric Vehicles (PHEV) offer all benefits of an electric drive without any loss of comfort and thus represent an (intermediate) solution already today.

1 Introduction

In order to achieve a drastic cut in CO_2 -emission according to the specifications of the IPCC (Intergovernmental Panel on Climate Change) it is required to improve efficiency in all sectors and to decrease CO_2-levels from electricity generation; however, these means alone do not suffice. In view of the fact that currently more than 30 % of German global emissions are generated locally by the transportation sector, residential heating and small consumers, it is essential to abandon oil and gas in favour of potentially CO_2-free final energy carriers in order to meet climate targets in the long run. Two end energy carriers are suitable and under consideration to meet these objectives: electricity and hydrogen.

By means of selected examples of use, we would like to show the advantages and disadvantages of an increased use of electricity and hydrogen in the mobility-sector. The assessment is based on a system-oriented approach and considers its upstream processes as well as cost, climate-protection and practical aspects. The statements, further considerations and assessments in this study are based on the results of the correspondent study [1] conducted by the Fraunhofer-Institute for Systems and Innovation Research in cooperation with the Ludwig-Bölkow Systemtechnik GmbH on behalf of RWE.

2 Scope of Research and Assumptions

In order to ensure a sensible comparison between electricity and hydrogen, we only compare process chains with the same primary energy carrier (e. g. natural gas) and for similar applications - under consideration of equal means and routes of transport. Our study deals with small town cars, compact medium-sized vehicles, delivery vehicles, city busses and -

exemplary - passenger boats for inland waterways, but also Plug-in Hybrid Electric Vehicles (PHEV). The above-mentioned fields of application are compared to conventional applications using fossil fuels.

Our study is based on two time frames:

2015 – Market launch of the new technologies: We assume that hydrogen and electricity are produced at today's state of technology. The partly nationwide hydrogen supply is realised via on-site electrolysers and steam methane reforming (SMR) at gas stations, all systems operating at rated capacity. It is furthermore assumed that by 2015 approximately the first 20,000 vehicles with electric- and hydrogen-drive have been launched on the market.

2030 – The new technologies have been established: The new electricity- and hydrogen-based technologies have been established on the market and a hydrogen grid is available. Hydrogen is produced at central plants, often with Carbon Capture & Storage (CCS). Compared to 2015, the German Electricity Mix has reduced its CO_2 -emission by almost 50 % (427 g/kWh_{el} → 233 g/kWh_{el}). We furthermore assume that by this time all vehicles are in commercial mass-production (> 500,000 vehicles per year).

Natural gas, lignite, wind and the German electricity mix are analyzed as sources to provide electricity and hydrogen, while steam methane reforming, lignite gasification and electrolysis are considered as means to generate hydrogen. We start our comparison of the process chains with the exploitation and production of the primary energy carrier, followed by its conversion into electricity or hydrogen and proceed with its transport and consumption (Well-to-Wheel; WtW). The following evaluation criteria are employed: energy-efficiency, greenhouse gas emissions, fuel costs and total cost of ownership as well as quality-related parameters (infrastructure, handling, cruising range and charging/refuelling times). The required power consumption and emission to build the factories and vehicles are not considered in this study. As a rule, cost are usually calculated without taxes and levies in order to ensure comparability while a sensitivity analysis shows the effect of today's fuel taxes. The required primary energy input and GHG-/pollutant emissions are calculated using the methods of international (IEA, Eurostat, ECE, Concawe) and German (AG Energie-bilanzen = German Working Group on Energy Balances) organisations.

3 Comprehensive Results from Process Chain Analysis

On the basis of the above-mentioned approach, we can firstly draw some general conclusions when comparing electricity and hydrogen. For the medium-sized compact class with a VW Golf as reference vehicle we assume the following: cruising range of Battery Electric Vehicle (BEV) = 150 km, Fuel Cell Electric Vehicle (FCEV) = 500 km, annual number of kilometres travelled = 14,200 km.

3.1 Energy efficiency

Starting with the same primary energy carrier and similar vehicle, electricity production requires less energy than hydrogen throughout the whole process chain (see figure 1). This is obviously the consequence of energy losses resulting from the electrolysis of water, as the secondary energy carrier has to be converted twice (electricity via electrolysis → hydrogen → hydrogen via fuel cell → electricity). For all processes the energy consumption of the H_2 -

chain depends on the prevailing application (H_2 -storage with 70 MPa). For H_2 production paths that are not based on electrolysis the energy consumption with on-site SMR will be approx. 20 - 55 % (by 2015) and with central SMR + pipeline or lignite gasification about 7 - 12 % higher than for the direct electricity chain.

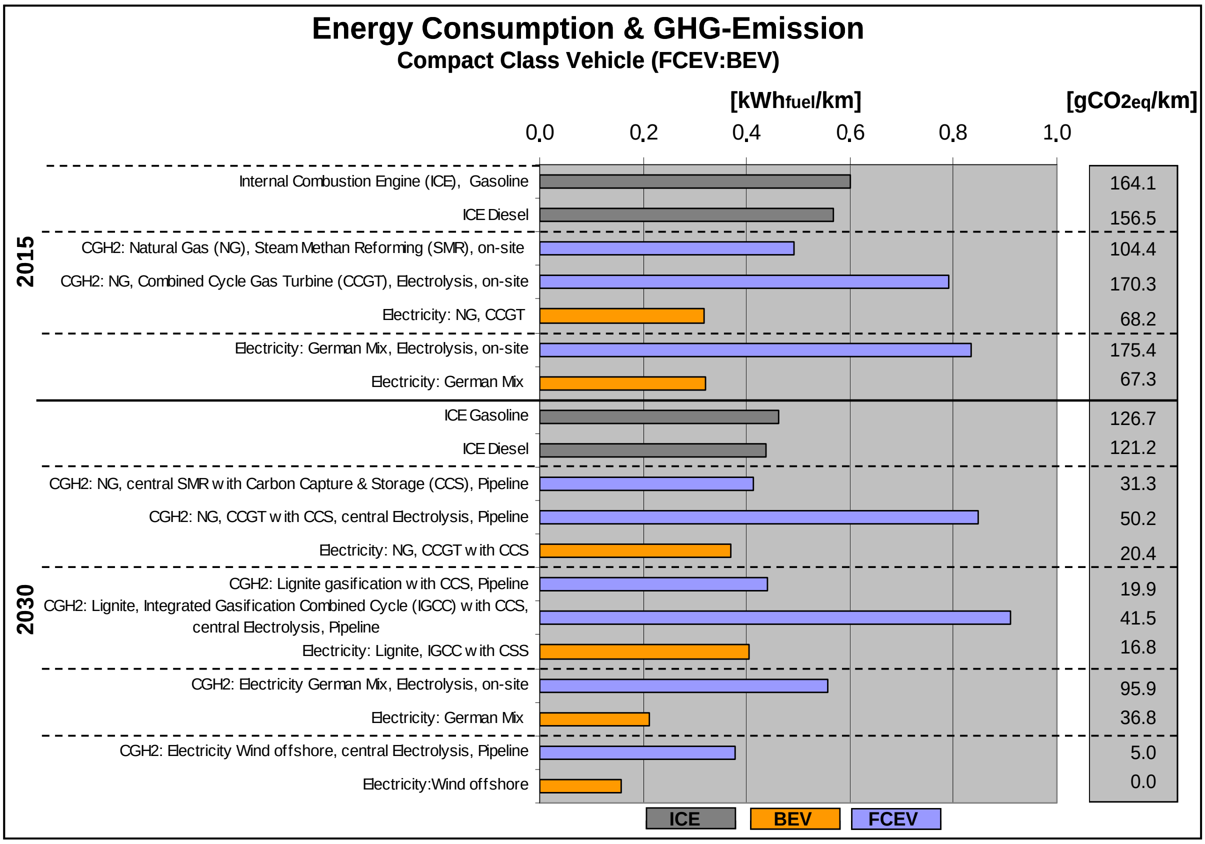

Figure 1: **Energy consumption and GHG-emissions for different production pathways but identical vehicles.**

3.2 Greenhouse gas emissions

Thanks to its high efficiency, the electricity path requires less fossil primary energy and thus CO_2-emissions are considerably reduced (compare figure 1).

The Well-to-Wheel comparison, based on natural gas as primary energy carrier, reveals that a compact-class BEV with electricity from a gas and steam plant emits 68/20 g_{CO2eq}/km (without/with CCS), while a FCEV with H_2 from steam methane reforming emits 104/31 g_{COeq}/km (without/with CCS) – which is about 50 % more. A FCEV with H_2 from electrolysis (German electricity mix and electricity from a gas and steam plant in 2015) emits even more GHG than a vehicle with diesel- or gasoline-engine (ICE). Due to the continuous reduction of CO_2-levels, the German electricity mix will contain distinctively less CO_2 in 2030 than in 2015 and will thus also have a corresponding effect on the H_2 electrolysis path (175 g/km → 96 g/km). The CO_2eq emission of the corresponding electricity path for a BEV will go down from 67 g/km (in 2015) to 37 g/km. This value corresponds to approx. 30 % of the GHG-emission of a comparable combustion engine in 2030. Also FCEVs will emit less GHG than conventional vehicles by 2030.

3.3 Energy costs

Due to their high efficiency, BEVs will result in lower fuel costs per 100 km than diesel-/gasoline-and H_2-vehicles by 2015 - no matter if taxes and levies are considered or not (figure 2).

3.4 Total cost of ownership

Figure 3 shows the total cost for the operation of comparable compact class vehicles with diesel-/gasoline-, hydrogen- and electric drives. For 2015 we expect that expenses (incl. taxes) for BEVs will be 10 - 12 % above those for conventional vehicles, while the expenses for FCEVs will even be 35 - 50 % higher. With respect to the uncertainty resulting from the long forecast period (based on today's taxes and levies) the costs for FCEVs are still above (5 - 16 %) the expenses for a vehicle with diesel engine. A BEV will cost approx. 10 % less than a vehicle with diesel engine.

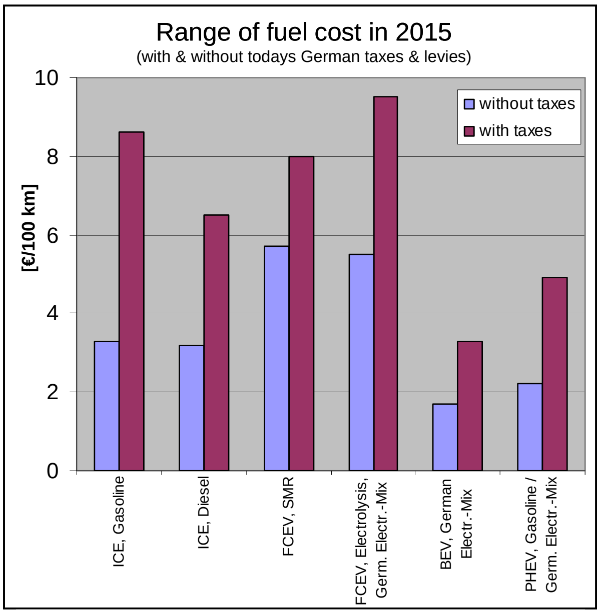

Figure 2: Range of fuel cost.

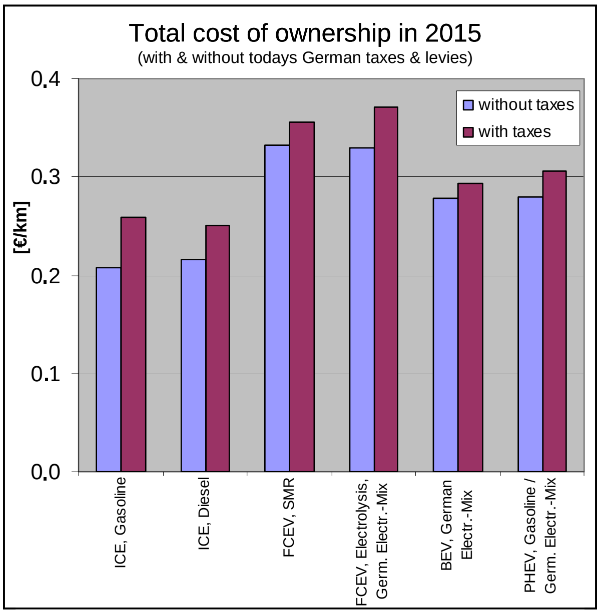

Figure 3: Total costs of ownership.

3.5 Infrastructure

There is a nationwide power grid and the gradual development of the charging infrastructure for BEVs (especially in the private and semi-public sector) may be realised at much lower costs than a complete new H_2-supply infrastructure – which would be required. The initial sharp increase in expenses, entailed by the development of a hydrogen infrastructure, will go down as soon as a nationwide infrastructure is available.

3.6 Handling

Every user knows how to handle electricity, whereas the broad public is not yet experienced in dealing with hydrogen as energy carrier.

In contrast to the above-mentioned benefits of electricity towards hydrogen, electricity still shows the following disadvantages in the mobility sector.

3.7 Cruising range

Today the cruising range of a BEV with a suitable battery size amounts to less than 200 km and is thus still lower than the range of a FCEV (> 400 km). However, we expect battery capacities – and thus cruising ranges – to improve further within the next few years.

3.8 Charging time/fuelling time

Today, the charging time of BEVs is considerably longer (> ½ h) than the fuelling time of vehicles with gasoline-/diesel engine (< 3 min.) or FCEVs (< 5 min.). However, they may easily be charged at any power outlet – no matter if at home or at work – while the vehicle is parked.

3.9 Interim conclusions

Due to their long charging time and the resulting loss of time and comfort in long-distance traffic, we would estimate that initially BEVs will rather be used for short distances or by commuters than in long-distance traffic (larger passenger cars, delivery vehicles, busses etc.). We assume that FCEVs have an advantage towards BEVs in the long-distance sector; but we do not yet know whether further progress in battery development could compensate this benefit. However, with Plug-in Hybrid Electric Vehicles (PHEV) we already today offer vehicles with a combined drive (battery and a small but efficient combustion engine) providing most of the above-mentioned advantages of a BEV without any loss of comfort.

Thus PHEVs may build a bridge in the long-distance segment to future quick-charging BEVs and FCEVs.

4 Further Fields of Application

4.1 Delivery vehicles

This study considers delivery vehicles with an admissible overall weight between three and five tons that are mainly used in urban delivery traffic. Our calculations (according to the above-mentioned pattern) use the example of a Mercedes Benz "Sprinter 316 or 316 CDI".

Like passenger cars also light duty vehicles (LDV) benefit more from electricity than from hydrogen with regard to energy efficiency, GHG-emission and expenses. Due to their characteristic field of application, the short cruising range still is an important disadvantage in this sector. However, battery replacement concepts, PHEVs or quick-charging batteries might solve this problem and should therefore be part of further research.

4.2 Busses

We have taken the Daimler “Citaro” as an example for our research in the bus-sector.

In this vehicle category, FC-buses (Citaro FuelCELL-Hybrid) already exist but no comparable model with battery electric drive. We have therefore calculated the current consumption for a fictive BE-bus with the aid of literature data from a trolley bus. Also in the bus-sector, electricity is more favourable than hydrogen with regard to energy efficiency, GHG-emissions and expenses. However, if the bus only runs on electricity, a battery of around 6 tons (state of technology in 2015) would be required to cover the distance of up to 250 km a bus travels per day. Compared to busses with a conventional drive, today’s FC-busses weigh around 2 tons more. Innovative approaches to reduce the battery weight - such as battery replacement concepts at turning points, inductive charging at bus stops or special PHEV-solutions are available but require more detailed research. A final analysis will have to show if and under what (e. g. regulatory) conditions the above-mentioned BE- and FC-bus concepts meet the requirements for an economical application in local public transport.

4.3 Passenger boats

Till December 2009 the passenger boat “Alsterwasser” operated in Hamburg was the only ship of this category with a hydrogen fuel cell drive throughout the world. Also a passenger boat with electric drive ("Alstersonne”) has been developed, which may however not be compared to the "Altsterwasser" with regard to design, weight and engine output. On the basis of a model calculation, comparing the consumption of a diesel-electric drive with a FC-drive, we learn that also in this sector electricity looks like the better choice: The energy consumption of an electric drive (German electricity mix) would be 34 % lower and the GHG-emissions would even be 50 % lower compared to a diesel-electric drive (in 2015). Like for commuter-BEVs, battery-electric drives would be suitable for short-distance passenger boats whereas FC-drives would be a good choice for larger long-distance transport ships.

5 Conclusion

With regard to the applied criteria (energy efficiency, GHG-emission and expenses), electricity as a rule reveals considerable advantages over hydrogen. Still, batteries have a lower energy storage density than hydrogen does so that today’s BEVs offer lower cruising ranges than FCEVs. Also the prolonged charging time of BEVs compared to FCEVs might have a negative effect on user comfort – which may, however, be reduced or even compensated by a future development of battery storage and fast-charging technology. Due to the above-mentioned advantages of electricity, it is likely that battery-electric cars will rather be applied in the short-distance segment where vehicles are only rarely used for trips of more than 100 to 200 km – and thus normally charged at home or at work. On the other hand, the FC-drive is presently ahead of the game for user groups or market segments where distances beyond 200 km are travelled. However, PHEVs with their battery (suitable battery size for standard distances) and small, economical combustion engine, provide already today all benefits of a BEV and the same user comfort (cruising range, charging/ refuelling time) as conventional cars.

Commercial vehicles are bigger and heavier than passenger cars, and, as a rule, drive long distances, cope with high payloads and remain in use for a sustained period of time. As long as the respective expenses for such projects are competitive with regard to FC- and hydrogen applications, battery-electric vehicles may still be applied in commercial vehicles, as (combined-) solutions like battery-change systems, inductive charging at bus stops (for busses) and PHEVs may help to meet the above-mentioned requirements. Vehicles with hydrogen drive will also in the long run be suitable for areas where combustion engines (gasoline and gas) are not allowed and where no power grid connection is available.

Abbreviations

BE	Battery Electric
BEV	Battery Electric Vehicle
CGH_2	Compressed Gaseous Hydrogen
CCS	Carbon Capture & Storage
DoD	Depth of Discharge
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LDV	Light Duty Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
SMR	Steam Methane Reforming

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