# Comparative Life-Cycle Cost Analysis of Hydrogen Fuel Cell Vehicles

B. Gnörich

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 6: Stationary Applications / Transportation Applications
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-6
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-656-9

# Comparative Life-Cycle Cost Analysis of Hydrogen Fuel Cell Vehicles

**Bruno Gnörich**, Institut für Kraftfahrzeuge, RWTH Aachen University, Aachen, Germany

## 1 Introduction

Anthropogenic energy consumption has been rising steadily for centuries, ever since fossil fuels became available on a larger scale. It has become an accepted fact that in future renewable energy sources will again need to provide a growing share. This applies to all energy sectors but much of the responsibility is allocated to the transport sector. There, increasing efforts towards low- and zero-emission transportation indicate that a broader mix of primary energy sources will gain in significance, e.g. for the production of synthetic fuels. Furthermore, electric drivetrains will become available. Overall, these trends underline the necessity to observe the entire energy pathway with regard to the relevant parameters such as efficiency, emissions, costs or availability of energy conversion pathways. This paper describes technical and economical analyses of fuel cell electric vehicles and comprises corresponding comparisons with conventional vehicles. Starting point is a thorough analysis of hydrogen fuel production, transport and refuelling, followed by description of vehicles. Comparative life-cycle analyses of fuel cell and conventional vehicles are covered in the final section of this paper. They allow identifying vehicle concepts that are most promising in view of market introduction and long-term competitiveness.

A comprehensive publication with all details of this study will be available in late 2010, after the completion of the author’s dissertation at RWTH Aachen University, titled “Vergleichende Gesamtkostenanalyse von Brennstoffzellenfahrzeugen”.

## 2 Hydrogen Fuel

The analysis of hydrogen as a fuel should ideally include the entire energy pathway: production, distribution, storage, refuelling and conversion, comprising technical, environmental and economic issues. In view of existing studies in this field (e.g. EUCAR-CONCAWE), emissions have not been analyzed here. The main focus is set on technical aspects and costs of current systems. Detailed cost models have been used to calculate the cost for the provision of hydrogen [STE08] to end customers at fuelling stations. They take into account all relevant components, raw materials, labour and amortisation. Hydrogen can be produced from different sources, with hydrocarbons (steam reforming) and water (electrolysis) belonging to the most prominent pathways. Natural gas reformers are mature technologies and well adapted in most diverse technical processes. As a result, hydrogen produced from natural gas is comparably cheap at about 3.40 €/kg in a facility scaled to about 100 t/$H_2$ per day (Figure 1). Reformers for biomass use the same technology as the ones for natural gas but tend to be much smaller due to dispersed availability of biomass. Hydrogen production costs are therefore signifycantly higher, at about 6.30 €/kg. In both cases, primary energy accounts to most of the costs. Locations for electrolysers do not depend mainly on electricity production sites. Furthermore, hydrogen production via electrolysis can make use of intermittent primary sources such as wind and solar energy. With electricity priced at 0.10 €/kWh, hydrogen can today be produced at costs of roughly 9 €/kg. However, solar electricity is much more expensive, taking into account the poor full load ratio of 20% in central and southern Europe. Solar hydrogen costs are at least 17 €/kg. Wind power plants yield more full load hours (up to 45%) and therefore allow for cheaper electrolysis for hydrogen priced at about 4.50 €/kg. Coal-fired power plants tend to be cheap with regard to electricity production if CCS is not included in the process. However, if $CO_2$ is to be separated and sequestrated, they become as expensive as their solar-powered counterparts.

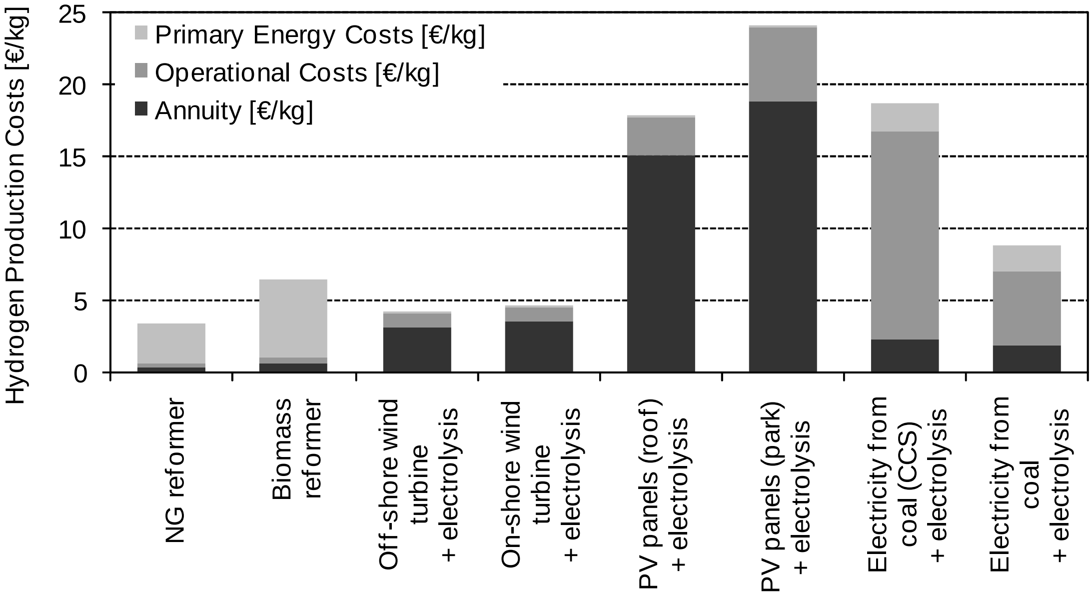

**Figure 1: Hydrogen production costs for different primary energy pathways.**

Hydrogen distribution can be realised continuously via pipelines or intermittently by different surface transport modes (truck, rail, ship). In pipelines, it is usually compressed to about 100 - 150 bar and adds about 0.80 €/kg for a transport distance of 500 km, provided that the pipeline yields a throughput of more than 70 t/d. Technically, they are similar to natural gas pipelines. Compressed hydrogen transport by truck trailers is preferred if the required transport capacity is low, and costs are about 0.50 €/kg for transport distances of up to 50 km. At higher transport volumes, liquefied transport is cheapest and costs about 1.20 €/kg for a transport distance of 200 km (Table 1).

**Table 1: Cost for the provision of hydrogen, including transport and dispenser.**

| | | Transport | | |
|---|---|---|---|---|
| | | Tube trailer (50 km) | LH2 (truck) (200 km) | Pipeline (500 km) |
| Sales price, incl. profit margin (20%) and VAT (19%) [€/kg $H_2$] | NG reformer | 5.89 | 6.89 | 6.32 |
| | Biogas reformer | 10.24 | 11.24 | 10.66 |
| | On-shore wind turbine, electrolysis | 7.50 | 8.50 | 7.93 |
| | Off-shore wind turbine, electrolysis | 6.93 | 7.93 | 7.36 |
| | PV panels (roof), electrolysis | 26.40 | 27.40 | 26.82 |
| | PV panels (park), electrolysis | 35.37 | 36.37 | 35.80 |
| | Electricity from coal, electrolysis | 13.74 | 14.74 | 14.17 |
| | Electricity from coal (CCS), electrolysis | 27.54 | 28.54 | 27.97 |
| Incl.: transport cost and fuelling station [€/kg $H_2$] | | 1.14 | 2.14 | 1.71 |

## 2.1 Hydrogen-powered vehicles

Hydrogen fuel cell vehicles are electric vehicles that have a fuel cell acting as an on-board electricity generator. As a consequence, the drivetrain investment cost of such vehicles consists not only of hydrogen storage and fuel cell system, but also contains the electric machine and potentially batteries or supercapacitors. All types of hybridization have been showcased in the past. Today, almost all fuel cell passenger vehicles are powered by PEM fuel cells operating at relatively low temperature (<100°C). The FC system can be manufactured for about 70 €/kW (80 kW system, [CAR05]). In this example, the total drivetrain cost is approximately 12,500 € (156 €/kW) and includes the electric machine (50 €/kW) and 700 bar CGH storage (capacity 5.5 kg, 20 €/kWh). The drivetrain can easily be configured in a hybrid layout with batteries or supercaps. The fuel cell can then be scaled down, potentially leading to reduced investment costs while retaining the vehicle performance. The operating costs represent another part of the vehicle's total cost of ownership. Those include primarily the cost of hydrogen as described before and servicing costs on a €/km basis.

If a vehicle uses 1 kg / 100 km, then the running cost ranges from about 8 € / 100 km for hydrogen from natural gas to 38 € / 100 km for hydrogen from PV parks. Servicing costs are estimated to be 0.02 €/km (Figure 2).

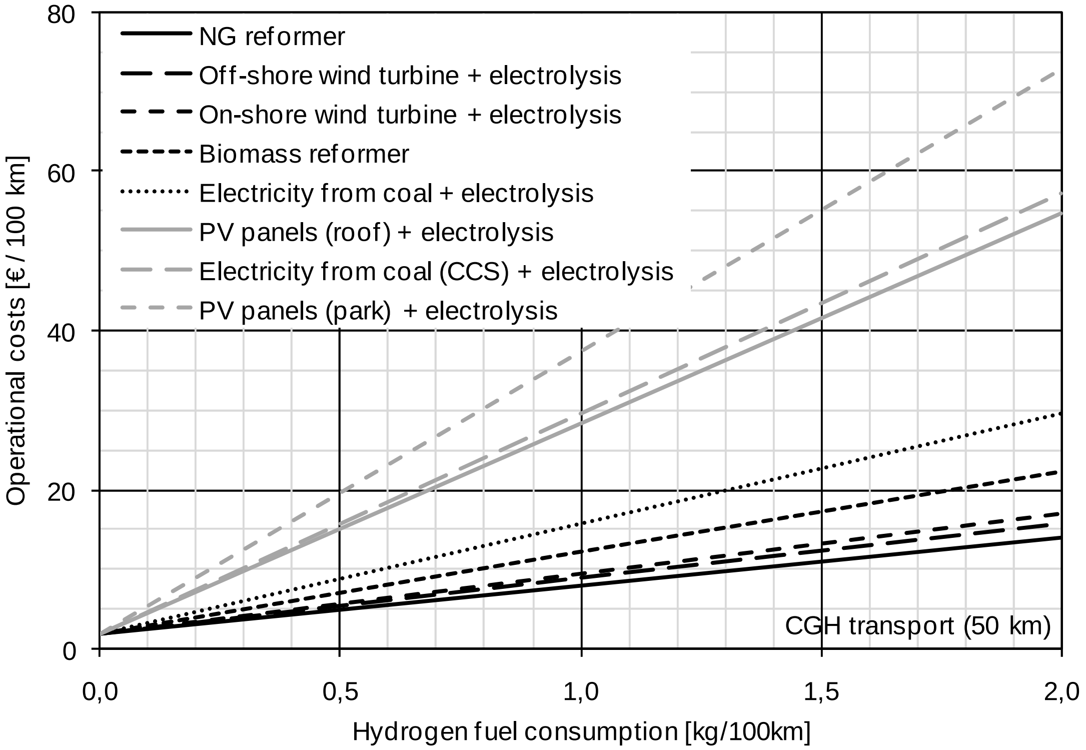

**Figure 2:** **Operating costs of hydrogen fuel cell vehicles as a function of hydrogen consumption and provision pathway.**

## 3 Sensitivity Analysis of Fuel Cell Hybrid Electric Vehicles

It is obvious that vehicle costs strongly depend on the hydrogen fuel consumption. As a result, the optimization of drivetrain efficiency adds to any investment cost benefit achieved through technological breakthroughs. Therefore, the analysis of diverse drivetrain concepts is a major part of this study. Non-hybrid and hybrid vehicle concepts in different vehicle classes have been analyzed with regard to their performance and their efficiency in the NEDC (New European Driving Cycle). A detailed simulation model was developed to calculate the relevant data. Basic fuel cell vehicles without hybridization achieve a drivetrain efficiency of 30 to 38% (Table 2). If combined with an advanced energy management system, the drivetrain efficiency can reach 60%, an increase of up to 50% compared to non-hybrid versions. The electric machines are individually scaled according to the power output of fuel cell, battery and supercapacitor. The vehicle mass is also determined based on the used components.

**Table 2: Efficiency (in %) of hydrogen FC vehicles in different vehicle classes (NEDC).**

| | | Compact class | | | | Medium-sized | | | | Luxury class | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hybridisation [kWh] | | Stack power [kW] | | | | | | | | | | |
| Battery | Supercap | 30 | 50 | 70 | 90 | 50 | 70 | 90 | 150 | 70 | 90 | 150 |
| - | - | | 30.3 | 32.1 | 33.3 | | 32.7 | 33.9 | 35.8 | | 35.8 | 38.2 |
| 0.5 | - | 41.3 | 44.5 | 45.2 | 46.9 | 44.7 | 47.0 | 48.7 | 54.6 | 53.2 | 55.2 | 59.8 |
| 2.0 | - | 46.2 | 48.6 | 51.0 | 52.8 | 52.0 | 52.3 | 54.1 | 58.5 | 56.6 | 58.4 | 62.6 |
| - | 0.15 | 42.1 | 45.2 | 47.2 | 48.9 | 46.0 | 48.1 | 49.8 | 54.0 | 52.7 | 52.6 | 56.6 |
| - | 0.45 | 41.9 | 44.8 | 46.7 | 48.3 | 45.3 | 47.3 | 48.9 | 52.8 | 51.5 | 53.0 | 55.7 |
| - | 0.71 | 39.8 | 43.9 | 46.2 | 46.3 | 45.2 | 47.2 | 49.3 | 53.1 | 51.5 | 53.1 | 56.2 |

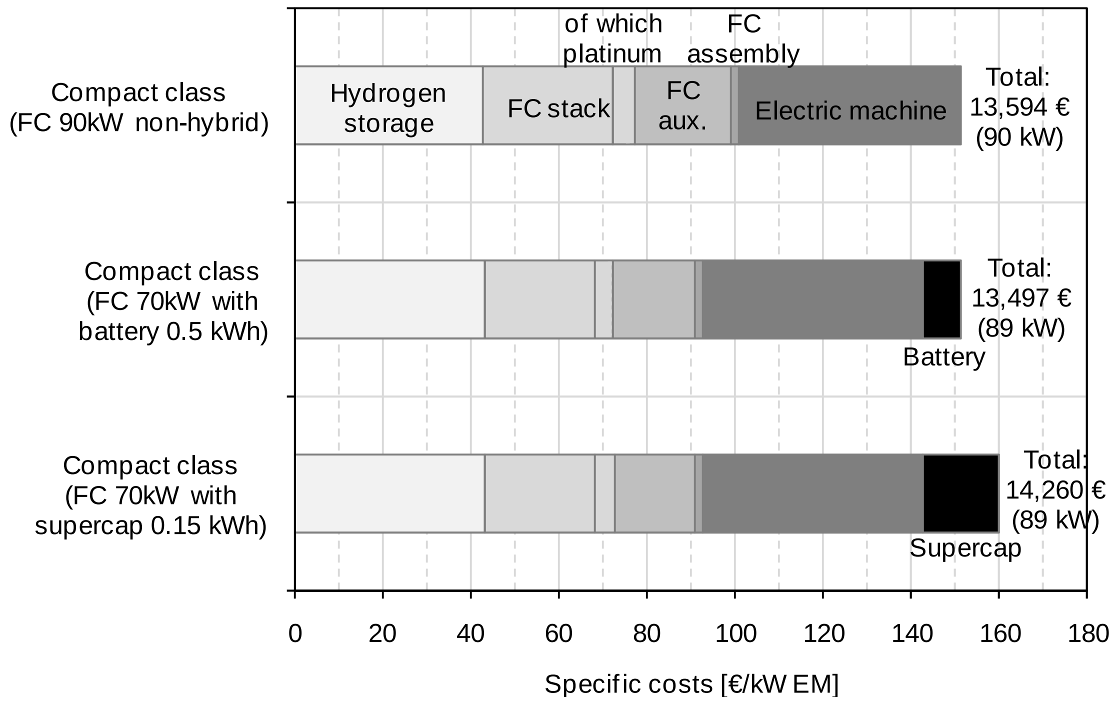

**Figure 3: Drivetrain costs for different FC vehicles (Compact class).**

Drivetrain costs have been calculated for every vehicle. Costs for non-hybrid vehicles consist almost equally of the costs for storage, fuel cell system and motor (Figure 3). The hybridisation leads to a reduced share of the fuel cell system. In some cases, total drivetrain costs do not rise despite the hybridisation. Since the hybridisation increases the efficiency, the total cost of ownership is lower than for non-hybrid vehicles, regardless of the cost for hydrogen. In case of higher drivetrain costs (e.g. in case of some hybrids with supercapacitors or “triple hybrids”), the cost benefit depends on the mileage / amortisation target.

## 4 Comparative Life-Cycle Analysis

Comparisons to conventional vehicles are vital for the success of fuel cell vehicles. As a final part of this study, a number of conventional vehicles were compared to the simulated fuel cell vehicles. This comprised the comparison of performance and costs. As a starting point for these final analyses, a performance indicator was developed to quantify the technical comparability of vehicles. It takes into account the acceleration, top speed and driving range, but not the costs. The TCO of the conventional vehicles is calculated using their respective drivetrain costs and running costs over a given amortisation distance (e.g. 200,000 km). The resulting value is then converted into hypothetical FC drivetrain costs and hydrogen fuel costs necessary for equal costs of the compared vehicles. It can be represented as a straight line in a hydrogen fuel cost vs. drivetrain cost diagram (Figure 4).

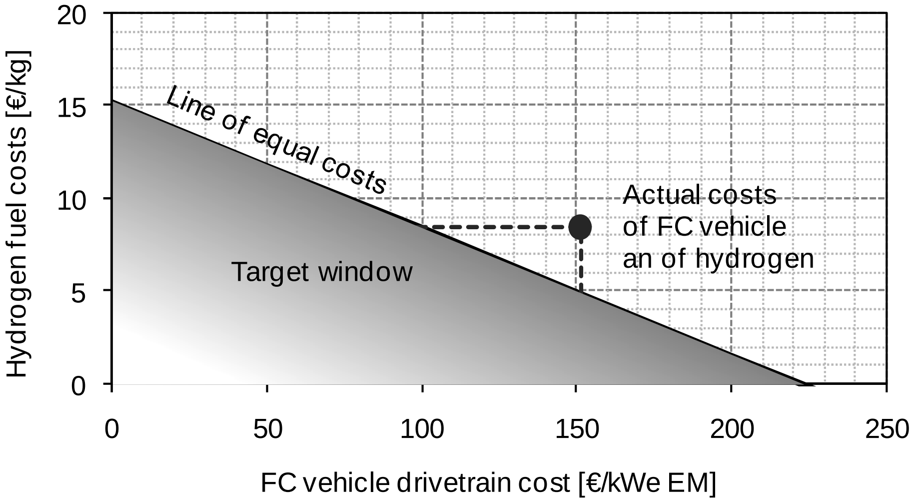

**Figure 4:** **Line of equal costs for a given conventional vehicle and actual hydrogen costs / FC vehicle costs marked as a dot.**

The actual FC vehicle can be marked as a dot in this diagram, as both its drivetrain costs and the cost for hydrogen have been determined earlier. If the dot is below the line of equal costs, the FC vehicle is cheaper than the conventional vehicle. It is more expensive if the dot is above the line. This representation of costs makes it easy to identify the required cost reduction for either hydrogen or the drivetrain in order to reach the same total costs as for the conventional vehicle. The slope of the line depends on the hydrogen fuel consumption and the amortisation distance. Rising costs for conventional fuels lead to a constant increase of the line of equal costs. On the other hand, the reduction of FC vehicle costs result in the dot moving leftwards closer to the line, and in case of changing hydrogen costs it moves vertically. As an example, the cost influence of the FC system is shown in Figure 5. In this case, even if the FC system did not cost anything, the vehicle would still not be competitive due to high costs for the hydrogen storage and the electric machine. The diagram on the right-hand side illustrates the effect of improved hydrogen fuel economy.

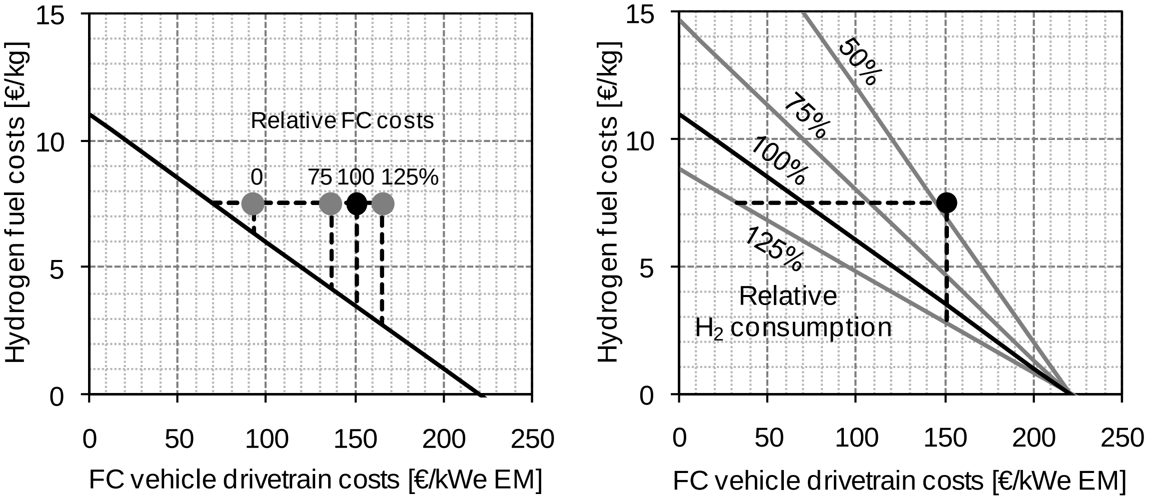

**Figure 5: Cost comparison for different FC system costs (left) and different hydrogen fuel consumptions (right).**

It becomes obvious that in this case it makes more sense to look at ways to improve efficiency than to reduce FC system costs.

## 5 Conclusion

The rising number of FC vehicles presented in recent years underlines the assumption that this technology is well under control in mobile application. However, market readiness is a completely different story due to high costs of hydrogen tanks, electric machines and FC systems. Infrastructure problems also persist and need to be addressed. Nonetheless, major OEMs and hydrogen producers recently agreed to aim for a noteworthy FC vehicle population by 2015. Current activities concerning battery-powered electric vehicles charged from the grid are not competing with FC vehicles, but yet another backbone towards the ultimate goal: sustainable and eco-friendly mobility.

## References

[1] GNÖRICH, B., *Vergleichende Gesamtkostenanalyse von Brennstoffzellenfahrzeugen*. Dissertation, RWTH Aachen University, Aachen, 2010 (publication due Q4 2010)

[2] STEINBERGER-WILCKENS, R., LINNEMANN, J., TRÜMPER, S., *Cost models for current and future hydrogen production*. Report D2.4 of EU FP6 project Roads2HyCom (SES6-019723), Oldenburg, November 2008

[3] CARLSON, E., KOPF, P., SINHA, J., SRIRAMULU, S., YANG, Y, *Cost Analysis of PEM Fuel Cell Systems for Transportation*. NREL/SR-560-39104, TIAX LLC, Cambridge/Massachussetts, September 2005