Efficiency of Hydrogen Fuel Cell, Diesel-SOFC-Hybrid and Battery Electric Vehicles

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Morgenacherstrasse 2F
CH-5452 Oberrohrdorf
October 20, 2003

Hydrogen is a synthetic fuel. At least the heat (enthalpy) of formation ($\Delta_f H^0$ = 286 kJ mol^{-1}) must be invested for its "fabrication" from water by electrolysis. This number corresponds to the Higher Heating Value HHV (= 142 MJ kg^{-1}) of hydrogen. According to the energy conservation principle, this is the true energy carried by hydrogen gas at 25°C. Consequently, for any known process of recombination of hydrogen and oxygen to water, the energy efficiency must be related to the original energy input or the Higher Heating Value HHV of the synthetic fuel. The widespread use of the Lower Heating Value LHV may be a convenient convention, but it is not supported by physics. In fact, the use of the Lower Heating Value for hydrogen produced by electrolysis (and other means) violates the energy conservation principle. Comparative studies of competing fuel options including hydrogen are meaningful and fair only if the analyses are based on the Higher Heating Values HHV of all energy carriers considered.

According to Faraday's Law the heat of formation $\Delta_f H^0$ of hydrogen can also be expressed as an electrochemical potential ("standard potential")

$$U_{00} = - \Delta_f H^0 / n_e F = 1.48 \text{ Volt}$$

with n_e = 2 being the number of electrons participating in the conversion and F = 96,485 Coulomb mol^{-1} the Faraday constant.

Only a fraction of the heat of formation $\Delta_f H^0$ is available for reversible energy conversion in fuel cells. This fraction is given by the Gibbs Free Energy $\Delta_f G^0$ = 237 kJ mol^{-1} for water at 25°C. Consequently, the theoretical voltage required to split water at 25°C by electrolysis is 1.23 Volts.

In fuel cells gaseous hydrogen is combined with oxygen to water. This process is the reversal of the electrolysis of liquid water and should provide an open circuit voltage of 1.23 Volts per cell. Furthermore, by definition of the Gibbs Free Energy, the ideal open circuit voltage of fuel cells decreases with increasing temperature.

Because of polarization losses at the electrode interfaces the maximum voltage observed for polymer electrolyte fuel cells is between 0.95 and 1.0 Volt. Under operating conditions the voltage is further reduced by ohmic resistance within the cell. A common fuel cell design voltage is 0.7 Volt, but the value may change between 0.6 and 0.8 Volt depending on the electric current drawn from the electrochemical reaction. Load fluctuations are typical for fuel cells in cars. The mean cell voltage of 0.75 Volt may be representative for standard driving cycles.

Consequently, the average energy released by reaction of a single hydrogen molecule is equivalent to the product of the charge current of two electrons and the actual voltage of only 0.75 Volt instead of the 1.48 Volt corresponding to the real energy content of hydrogen. In automotive applications PEM fuel cells may reach mean voltage efficiencies of 0.75V / 1.48V = 0.50 or about 50%.

However, there are more losses to be considered. The fuel may not be fully utilized. This is not an issue for closed end hydrogen systems, but may contribute significantly to the losses in other types of fuel cells. Also, fuel cell systems consume part of the generated electricity. Typically, automotive PEM fuel cells consume 10% or more of the rated stack power output to provide power to pumps, blowers, heaters, controllers etc. Again, drive cycles have to be considered. At low power demand the fuel cell efficiency is improved, while the relative parasitic losses increase. The part load advantages are lost by increasing parasitic losses. Let us assume that for all driving conditions the net power output of an automotive PEM fuel cell system is about 90% of the power output of the fuel cell stack.

Depending on the chosen drive train technology, the DC power is converted to frequency-modulated AC or to voltage-adjusted DC, before motors can provide motion for the wheels. Energy is always lost in the electric system between fuel cell and wheels. The overall electrical efficiency of the electric drive train can hardly be better than 90%.

By multiplying the efficiency numbers one obtains for the maximum possible tank-to-wheel efficiency of a hydrogen fuel cell vehicle 0.50 * 0.9 * 0.9 = 0.40 or 40%. This is significantly less than the 60% used by the promoters of a hydrogen economy and hydrogen fuel cell vehicles.

But hydrogen has to be generated by electrolysis. Steam reforming of natural gas provides no lasting solution, because in comparison with natural gas vehicles the overall efficiency cannot be improved, nor can the emission of greenhouse gases be reduced by the conversion of natural gas into synthetic gaseous hydrogen. Carbon dioxide sequestration is not even considered at this time.

However, in a Sustainable Energy Economy electric power from various sources will be used "fabricate" hydrogen by electrolysis of water. In this context, we assume a power-plant-to-hydrogen efficiency of 70% for water make-up and electrolysis near the source of electricity. Hydrogen gas has to be compressed or liquefied to make it transportable. The efficiency of compression is about 90%, that of liquefaction about 65%. Then hydrogen will be delivered to filling stations and transferred to vehicle tanks by road or pipeline. This takes about 10% of the HHV energy of the delivered hydrogen for gaseous, but only 6% for liquid hydrogen. At least 3% are needed for the transfer of gaseous hydrogen from a large storage tank at 100 bar into the high pressure tank of an automobile.

For a fuel cell car operated on gaseous hydrogen the following numbers are representative:

30% losses for water make-up and electrolysis: factor 0.70
10% losses for compression of hydrogen: factor 0.90
10% losses for distribution of gaseous hydrogen: factor 0.90
3% losses for hydrogen transfer: factor 0.97
50% for conversion to electricity in fuel cells: factor 0.50
10% parasitic losses for the hydrogen fuel cell system: factor 0.90
10% electric losses in the drive-train between battery and wheels: factor 0.90

The "power-plant-to-wheel" efficiency of a fuel cell vehicle operated on compressed gaseous hydrogen will be in the vicinity of 22%.

Using liquefied hydrogen does not improve the situation as the following numbers show:

30% losses for water make-up and electrolysis: factor 0.70
35% losses for compression of hydrogen: factor 0.65
6% losses for distribution of gaseous hydrogen: factor 0.94
1% losses for hydrogen transfer: factor 0.99
50% for conversion to electricity in fuel cells: factor 0.50
10% parasitic losses for the hydrogen fuel cell system: factor 0.90
10% electric losses in the drive-train between battery and wheels: factor 0.90

The "power plant-to-wheel" efficiency of a fuel cell vehicle operated on liquid hydrogen will be in the vicinity of 17%.

These numbers are certainly better than the drive cycle efficiency of yesterday's cars, but they compete with the high efficiency of modern clean Diesel passenger cars and commercial hybrid vehicles. Advanced Diesel-fuelled passenger vehicles now reach HHV drive cycle efficiencies of over 25%.

It is not the intent of this summary to present a precise analysis of all possible options of hydrogen use for transportation, but the results suggests that the numbers used in support of hydrogen programs should be checked carefully and corrected.

Finally, it might be useful to note that much higher efficiencies are obtained for hybrid electric cars with Diesel-fuelled solid oxide fuel cells as range extender (see "Solid Oxide Fuel Cells for Transportation, www.efcf.com/reports).

One obtains for a battery-SOFC hybrid vehicle and Diesel fuel:

12% losses between oil well and filling station: factor 0.88
50% HHV efficiency of SOFC with internal reforming and Diesel fuel: factor 0.50
5% parasitic losses for the SOFC system: factor 0.95
10% electric losses in the drive-train between battery and wheels: factor 0.90
20% losses for battery charging and discharging: factor 0.80
10% bonus for regenerative braking: factor 1.10

With these numbers the well-to-wheel efficiency of a hybrid electric car with SOFC range extender operated on Diesel fuel becomes 33%. Also, instead of Diesel from fossil resources a variety of natural or synthetic liquid, biomass-derived hydrocarbons (methanol, ethanol, bio-diesel etc.) can be used. The high well-to-wheel efficiency suggests that some thought should be given to this option, in particular, as this clean solution can be implemented within the existing fuel infrastructure.

Even more attractive are electric cars as suggested by the following number:

10% losses between power plants and homes: factor 0.90
8% losses in small home-based AC/DC battery chargers: factor 0.92
20% losses for battery charging and discharging: factor 0.80
10% losses in the drive-train between battery and wheels: factor 0.90
10% bonus for regenerative braking: factor 1.10

With these numbers the power-plant-to-wheel or wind-farm-to-wheel efficiency of an electric car with regenerative braking becomes 66%. This number indicates that the best option for local driving could be the electric commuting car with limited battery capacity for local runs. This might imply the introduction of a new mobility concept, but it does not require the creation of a hydrogen infrastructure. Family cars for longer trips would most likely become battery hybrids. Fuel cells or clean and efficient IC engine operated on biofuels could serve as range extender. But pure hydrogen is unlikely to be used for this purpose because of the known storage problems the synthetic fuel is not suited for long distance travel. Biofuels are more likely to provide the energy for range extension. The vision would suggest electric power for local and synthetic liquid hydrocarbons for distant travel.

Statements claiming hydrogen fuel cell vehicles to be the one-and-only or the best solutions for the future transportation applications certainly need further validation. With respect to atmospheric pollution the two alternative options presented above are as benign as hydrogen fuel cells. However, both promise to have a much higher overall efficiency and economy. This is one of the mandates for the outgoing fossil fuel era and for a future Renewable Energy Economy. The consumer has a choice.

About the Author
Ulf Bossel has earned his Diploma Degree in Mechanical Engineering at the Swiss Federal Institute of Technology (ETH) in Zurich and his Ph.D. at the University of California in Berkeley. He has served many years in the area of renewable energy and energy conservation. As an independent consultant he does not have to bend his back for salary or research contracts, but is free to voice his opinion in the ongoing energy discussion as advocate of physics and honesty.