

Verdict on the Hydrogen Experiment – an Update

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Introduction by **Andrew Ferguson**

On page 9 of OPT 2/1, namely the April 2002 issue of the *OPT Journal*, I accused *World Watch*, *The Ecologist* and *New Scientist* of being determined to maintain a Panglossian view of a 'hydrogen future'. In that piece, I made it clear that there was a weak spot in my assertion, because there was little information available regarding the performance of fuel cells; in particular, the extent to which they might improve on the internal combustion engine when used in a vehicle. That has changed with data from various sources, starting with an article about the prototype *Ford Focus Fuel Cell Vehicle* in *The Times*, by Anthony Browne, 17 October 2002. Then came data on a *Honda FCX*, retrieved for me by David Pimentel, from <www.fueleconomy.gov>, 5 December 2002. Lastly, confirmation came from an article edited by Paul Hudson in *The Telegraph*, 18 January 2003, which provided two consumption figures.

As it is the oft-repeated implication of the 'experts' that hydrogen plus fuel cells is a combination which will answer all our future energy problems, a spotlight on the matter is needed. So as to maintain maximum transparency, and also to keep some of the detail out of the main text and to allow space to cover some other points of possible interest arising from these reports, a more comprehensive analysis of them is given in Appendix A. However, while there may be various matters that are of background interest about using hydrogen as an energy carrier to power motor vehicles, by far the most important question is this: where is the energy to come from to make the hydrogen? To fully consider that point, some text is repeated from an earlier piece, which was titled simply *Verdict on the Hydrogen Experiment* (it dealt with burning hydrogen in an internal combustion engine rather than converting it in a fuel cell).

I should warn the reader that spelling is 'mid-Atlantic'! I use the word 'gasoline' rather than 'petrol', yet 'litre' rather than 'liter'. I only hope this will not cause offence on both sides of the Atlantic!

VERDICT ON THE HYDROGEN EXPERIMENT: AN UPDATE

by Andrew Ferguson

ABSTRACT: When a car is powered by hydrogen burnt in an internal combustion engine, it takes 3 litres of liquid hydrogen to move the car over the distance that 1 litre of gasoline would take a similar car. Drawing on some recent figures relating to the performance of prototype cars, in which the hydrogen is transformed into electricity in a fuel cell, this paper shows that these prototype vehicles used 2.3 litres of liquid hydrogen to achieve the same result

A fuel cell might lower the *overall* cost of using hydrogen as an energy carrier to drive a car (depending on how much more expensive than an internal combustion engine the fuel cell proves to be). However, this paper shows that cost is not the main question. In Iceland, where energy from hydroelectric and geothermal sources is easily available, it is clearly viable to manufacture the liquid hydrogen. For the rest of the world, the unanswered question is where the energy is to come from.

Looking at the overall energy transformation, it would take 9.14 kWh of electricity, = 32.9 MJ of electricity, to produce hydrogen with the same motive energy as 1 litre of gasoline (which has an energy density of about 33.5 MJ/litre). This almost equal requirement for energy is a viable proposition when renewable energy can be generated directly as electricity from renewable sources, as in Iceland, but generating the electricity from fossil fuels would call for the use of about $32.9 / 0.33 = \underline{99.7}$ MJ of fossil fuel energy, about three times the energy in gasoline, and that would be prohibitive both in consumption of fossil fuels and emissions of carbon dioxide.

Readers of the November/December 2000 issue of World Watch may recall the glow of a volcanic flare on its cover, with the words, *The Hydrogen Experiment: Descendants of the Vikings Embark on a Bold New Quest to Transform the World's Energy Economy*. But perhaps the significance of the following two nuggets of information did not fully register:

- 1) Iceland has been producing hydrogen since 1958: the plant “uses about 13 megawatts of power annually to produce about 2,000 tons of liquid hydrogen.”
- 2) In Iceland, the cost of electricity is \$0.02 per kilowatt hour (kWh), due to the availability of geothermal and hydro power.

Allowing for the fact that hydrogen burns more efficiently than gasoline when hydrogen is burnt in an *internal combustion engine*, 3 litres of liquid hydrogen will take a car as far as 1 litre of gasoline.^{T1} The greater efficiency of a fuel cell improves on that, and it takes only 2.3 litres of liquid hydrogen to achieve the same result (see Appendix A).

We can calculate the need for 9.1 kWh_e of electricity to produce 2.3 litres (160 gm) of liquid hydrogen (Appendix A); and that is the amount — when used in a fuel cell — of hydrogen needed to take a car as far as a litre of gasoline, i.e. it has the same ‘motive energy’.

Paying \$0.02 per kWh for electricity, the dollar cost of *the direct energy* needed to produce the 2.3 litres of liquid hydrogen — equivalent to a litre of gasoline — would thus be $9.1 \times \$0.02 = \underline{\$0.18}$. Note that when I say “equivalent to a litre of gasoline,” I mean equivalent when used in a fuel cell, although to save space I will not add that qualification on every occasion. The \$0.18 does not cover the transportation or storage of the hydrogen, or the *non-energy* costs of electrolysis and liquefaction. As a ballpark figure, to cover these other aspects, we can perhaps assign \$0.05 for each litre of liquid hydrogen. Thus, in Iceland, hydrogen should be deliverable at a cost of about $\$0.18 + (\$0.05 \times 2.3) = \underline{\$0.29}$, for the 2.3 litres that are equivalent to a litre of gasoline; or \$1.10 for an amount equivalent to a U.S. gallon of gasoline.

That is all splendid news for Icelanders. In the United Kingdom, when the cost of oil was around \$32 a barrel (\$0.20 per litre), the retail cost of gasoline was about \$1.20 per litre, or \$4.54 per U.S. gallon, of which about 75% was tax. So, in Iceland, the cost of liquid hydrogen, calculated as being 29¢ per litre of gasoline equivalent, would compare well with the *real* cost of gasoline, 30¢ per litre. Indeed, the Icelandic government could, assuming that the Icelandic taxpayer is as tolerant as the British, add on a 300% tax!

According to an article in *The Times*, U.K. electricity prices in October 2002 were languishing near record lows at US\$28 per MWh. However, energy companies were in such dire straits that they were having to close down capacity. Apparently the cost of generating electricity, using a gas-fired plant, was \$28 per MWh, rising to \$62 per MWh using older oil-fired plants. If we take \$35 per MWh as a price at which the generators would not be suffering too badly, that would be 3.5¢ per kWh, raising the cost of liquid hydrogen by about 50% compared to the previous calculation.^{T2}

However, outside Iceland, costs are only of background interest; what is more significant than cost is whether the electricity can be made available, and if so at what environmental cost.

Accounting for only the direct electrical energy used to produce the liquid hydrogen that would be needed to replace the gasoline currently being consumed, each person in the United States (281 million people as of 2000) would require 15,600 kWh/yr of electrical energy (which projects to 1.25 times the total electricity used in the USA).^{T3} Were you to suggest to Utility executives that they should be able to produce a significant proportion of this *extra* electricity, they would — especially in California — fall about laughing. We will be lucky, they would reply, to keep pace

with our population growth, which in the US is over 1% a year. Moreover, since natural gas supplies are peaking, we won't be able to do that for long.

The coal 'option'

The reason that we cannot resort to producing hydrogen from methane (CH₄) is the imminent scarcity of natural gas.^{T4} If there is to be a 'hydrogen future', then the energy needs to come from *renewable* resources. Yet the coal lobby is strong in America, so perhaps we should divert for a moment to think of using coal to produce the electricity needed. The calculations are in Appendix A. They show that using coal to generate electricity, in order to produce hydrogen by electrolysis, requires about three times as much energy as is contained in gasoline which has the same motive energy as the hydrogen produced. With coal having a higher carbon content than gasoline, the release of carbon dioxide would be considerably higher than three times as much.

While not germane to hydrogen production, another point to consider is the option of producing synthetic gasoline from coal, as was done in Nazi Germany and South Africa. According to the most recent data I have, the total carbon released from synthetic gasoline (including release during the conversion process) is 76% more than would be released from burning gasoline refined from oil.^{T5} The existing overload of atmospheric carbon, the large amount of coal needed, and falling ratios of energy output to energy input for coal (more energy needed to get the coal out as coal gets more difficult to access) combine to make it unlikely that synthesizing gasoline will be adopted on a wide scale.

Renewables

A favorite daydream of greens is to produce hydrogen from wind turbines, so let us survey wind energy potential. The American Wind Energy Association estimates that it would be possible to install, onshore and offshore, turbines with 355,000 megawatts of rated capacity. That might appear to be equivalent to about 355 fairly large power stations, but it is less than half of that, since the capacity factor (amount of output compared to rated output) of wind turbines, in the US, is probably about 25%, whereas coal-fired power stations usually operate at around 60%. Moreover, installation of the, for example, 355,000 turbines each of 1 MW capacity, and the task of connecting them together, would be a substantial undertaking, costing about 355 billion dollars. Once achieved, the turbines would supply only about 22% of current U.S. *electrical* demand — enough to satisfy 20 years of U.S. population growth.^{T6}

To summarize, it may be possible to overcome the disadvantages of hydrogen as an energy carrier (one is that its boiling point is -253°C), but producing it will only be possible for nations which have substantial resources of renewable energy. That excludes *everywhere* except Iceland.

Why has it been necessary to update the previous article in the April 2002 *OPT Journal*? The reason is because in that, it was only *suggested* that fuel cells would not change the picture significantly. I had no firm data to back that judgement. With facts on consumption using fuel cells in cars becoming available, it seemed necessary to close off another 'solution' espoused by pipe dreamers. Another thing I learnt from the article in the *Daily Telegraph* is that it takes about as much energy to

pressurise hydrogen to the high pressures, about 10,000 pounds per square inch, that are needed to achieve a useful energy density, as it does to liquefy it.

Finding the energy to make the hydrogen is the crux of the hydrogen problem, but Appendix A does cover more ground than that. One reason is to assist people who get the chance to test prototypes to ask the right questions about hydrogen. Asking questions may be helpful to the Ford motor company, which, according to Browne, spent US\$450 million in research and development, including \$2.5 million on the prototype car. If other manufacturers have been spending similar sums, it would seem advisable for them to give further thought to where the energy is to come from.

Conclusion

The wider conclusion to draw from this study is the one which often emerges from these pages: there are no easy solutions to capturing the power of the sun in 'real time'. The corollary is that the only path to a better future is to reduce human population to something like two billion — even that figure is in doubt, being about three times the number of humans alive when the fossil fuel age started, in 1750 AD.

Appendix A: background to the above analysis

While hydrogen consumption in a vehicle can be measured in terms of distance per kg, or litre (of liquid hydrogen), the figure has little meaning unless one can compare it to gasoline (petrol) consumption. The consumption implications becomes clear only when the amount of hydrogen is assessed in terms of how much hydrogen is needed to replace a litre of gasoline. Thus the first step is to have a benchmark for a conventional car of similar carrying capacity to the hydrogen prototypes. The general opinion appears to be that a conventional car of similar capacity to the prototypes would have a consumption of 14 km/litre (= 33 miles per US gallon or 40 miles per Imperial gallon). That is our benchmark.

Next we must review the fuel consumption figures of the four prototypes:

The Ford Focus Fuel Cell Vehicle reported on by Anthony Browne, in *The Times*, 17 October 2002, gave rather ill defined figures for consumption, saying only that the 4 kg of hydrogen it contained would take it "more than" 200 miles. To allow a margin of error, let us take this as meaning 220 miles (354 km).

If 354 km requires 4000 gms of hydrogen,
14 km would require $4000 \times 14 / 354 = \underline{158}$ gms.

A Honda FCX received a more precise appraisal at <www.fueleconomy.gov> (5 December 2002): 51 miles (82 km) per kg of hydrogen.

If 82 km requires 1000 gms of hydrogen,
14 km would require $1000 \times 14 / 82 = \underline{170}$ gms.

The Hydrogen 3 car produced by GM, and reported in the *Daily Telegraph*, 18 January 2003, provided two sets of figures. The first indicated that 3.1 kg of hydrogen would take the car 170 miles (273.5 km).

If 273.5 km requires 3100 gms of hydrogen,
14 km would require $3100 \times 14 / 273.5 = \underline{159}$ gms.

The other set suggested that 4.6 kg would take the car 250 miles (402.25 km).

If 402.25 km requires 4600 gms of hydrogen,
14 km would require $4600 \times 14 / 402.25 = \underline{160}$ gms.

Choosing a round figure from those data suggests that 160 gms of hydrogen will provide the same motive power (when transformed in a fuel cell) as 1 litre of gasoline. The volume of 160 gms of liquid hydrogen is 2.29 litres.^{T7} Thus in round terms we can say that, using a fuel cell, 2.3 litres of liquid hydrogen are required, to provide the same motive energy as 1 litre of gasoline. The amount of electrical energy needed to produce 2.3 litres is 9.1 kWh; and if the electricity had to be made by burning fossil fuel, then the energy required would be 27.6 kWh_{th}.^{T8}

Pressure problems

Reports on cars powered by fuel cell using hydrogen nearly always report the weight of hydrogen consumed or in the tank, but it is the volume and pressure that present the largest problem. In its most dense form, that is in liquid form, hydrogen has a density of 0.070 kg/litre (McGraw-Hill, p. 338 of Vol.1, 8th edition), and we have seen that 2.3 litres of liquid hydrogen are needed to replace a litre of gasoline.

Hydrogen liquefies at -253°C , and its critical temperature is -240°C . Above the critical temperature a gas can no longer hold its liquid form, so the pressure rises as the temperature rises. If liquid hydrogen, fully filling the tank, is allowed to warm up to 50°C , the pressure increases to 930 atmospheres, thus a robust container is required.^{T9} According to the *Daily Telegraph* article, edited by Paul Hudson, 18 January 2003, the *Hydrogen 3* car could operate either on (1) hydrogen pressurised at 10,000 psi (680 atmospheres) with a 'spun-carbon' tank, or (2) using liquid hydrogen. For the latter, it would appear, from the above, that the tank would have to be designed to cope (for special situations), with a a pressure of 930 atmospheres (though less if the tank is not fully filled).

The efficiency of the 'hydrogen - fuel cell' combination

Hydrogen has a heat content of 120 MJ/kg (McGraw-Hill, p. 338 of Vol.1, 8th edition), or 120 kJ/g, and we have calculated that 160 g of hydrogen has the same motive energy as 1 litre of gasoline (the figure is 210 g in an internal combustion engine).

So 160 g of hydrogen would have a heat content of $160 \times 120,000 = \underline{19.2}$ MJ (1 MJ = 1×10^6 joules).

Gasoline has an energy density of around 33.5 MJ/litre. Thus when used in a fuel cell, 19.2 MJ of hydrogen has the same capacity to move a vehicle as 33.5 MJ of gasoline. So it is $33.5 / 19.2 = 1.745$ as efficient (or 74.5% more efficient) than gasoline.

The foregoing analysis seems fairly cast iron. It would be interesting to know why manufacturers claim that the fuel cell is 90% efficient and a gasoline engine 30% (as stated in Browne's article), giving a ratio of 3.0, when the more relevant comparison is 1.745. Is there a confusion about the ability of a fuel cell to (a) produce electricity and (b) to produce mechanical energy?

The problem of finding the energy to produce the hydrogen

Now we have reached the crunch item! Where to find the energy? When driving a car powered by a fuel cell, about 2.3 times the volume of liquid hydrogen will be consumed as gasoline would be in a similar car. We have also noted that the energy used *at the point of consumption*, when converting hydrogen, is $1 / 1.745 = 57\%$ of what would be needed using gasoline. However, looking at the overall energy transformation, it would take 2.284×4 [kWh/litre] (endnote 3) = 9.14 kWh of electricity = $9.14 \times 3.6 \times 10^6 = \underline{32.9}$ MJ of electricity to produce hydrogen with the same motive energy as 1 litre of gasoline (which has an energy density of about 33.5 MJ/litre). This almost equal requirement for energy is a viable proposition when renewable energy can be generated as electricity directly from renewable sources, as in Iceland, but generating the electricity from fossil fuels would call for the use of about $32.9 / 0.33 = 99.7$ MJ of fossil fuel energy, about three times the energy in gasoline, and that would be prohibitive both in consumption of fossil fuels and emissions of carbon dioxide.

{T?} endnotes for *Verdict on the Hydrogen Experiment: an Update*

{T1} For the full calculation see endnote 2, p. 11 of *OPT Journal* 2/1, April 2002.

{T2} At \$35 per MWh, or 3.5¢ per kWh, compared to 2¢ per kWh, the *energy* cost would increase by a factor $3.50 / 2 = 1.75$.

So the increase in cost would be $\$(0.18 \times 1.75 + (\$0.05 \times 2.3)) / (\$0.18 + (\$0.05 \times 2.3)) - 1 = 46\%$, say 50%.

{T3} Calculation of electricity needed to produce 1 litre of liquid hydrogen:

First, drawing on the empirical data from Iceland

13 MW for a year = 13,000 kW for a year = $13,000 \times (24 \times 365) = \underline{113.9 \times 10^6}$ kWh_e.

2,000 t liquid hydrogen = 2×10^6 kg.

Liquid hydrogen has a density of 0.070 kg/litre (McGraw-Hill, p. 338 of Vol.1, 8th edition).

So 2×10^6 kg would occupy $2 \times 10^6 / 0.070 = 28.57 \times 10^6$ litres.

Thus energy expenditure per litre = 113.9×10^6 [kWh] / $28.57 \times 10^6 = 3.99$ kWh_e/litre.

Secondly, a theoretical evaluation of the energy needed to produce 1 litre of liquid hydrogen

Since electrolysis to produce hydrogen is 71% efficient, 1 kWh of electricity produces 0.71 kWh_{th} of hydrogen.

Since liquefaction uses 30% of the energy in the hydrogen,

the energy needed for liquefaction = $0.71 \times 0.30 = 0.213$ kWh_e.

Thus $1 + 0.213 = 1.213$ kWh_e is sufficient to produce, and liquefy, 0.71 kWh_{th} of hydrogen.

Thus $1.213 / 0.71 = \underline{1.708}$ kWh_e produces 1 kWh_{th} of liquid hydrogen.

The heat content of hydrogen is 120 MJ/kg (McGraw-Hill, p. 338 of Vol.1, 8th edition).

Liquid hydrogen has a density of 0.070 kg/litre (McGraw-Hill, p. 338 of Vol.1, 8th edition).

So 1 litre of liquid hydrogen has an energy content of $0.070 \times 120 = 8.4$ MJ = $8.4 \times 10^6 / 3.6 \times 10^6 = \underline{2.333}$ kWh_{th}.

Since it takes 1.708 kWh_e to produce 1 kWh_{th} of liquid hydrogen, the electricity needed to produce 2.333 kWh_{th} (1 litre or 70 g) of liquid hydrogen = 1.708 x 2.333 = 3.985, say 4.0, kWh_e.

Cross-check that 1 litre of liquid hydrogen requires 4.0 kWh_e

70 g (1 litre in liquid form) of hydrogen contains 2.333 kWh_{th}.

30% of this is the amount of electrical energy needed for liquefaction, i.e 2.333 x 0.30 = 0.70 kWh_e.

Since electrolysis is 71% efficient, to produce 2.333 kWh_{th} of hydrogen requires 2.333 / 0.71 = 3.286 kWh_e.

So total energy required to produce 70 g (1 litre) of liquid hydrogen = 3.286 + 0.70 = 3.986 kWh_e, say 4.0 kWh_e.

Replacing U.S. gasoline

A paper in the *Oil and Gas* journal by M.R. Simmons gave a figure, for US consumption of gasoline, of 8,286,000 barrels a day, as of March 2000. 8,286,000 x 365 = 3.02 billion barrels a year.

3.02 x 10⁹ barrels = 3.02 x 10⁹ x 42 x 3.785 = 480 x 10⁹ litres.

US population in 2000 was 281 million.

So per capita consumption = 480 x 10⁹ / 281 x 10⁶ = 1708 litres of gasoline per year.

Using a fuel cell, the amount of liquid hydrogen needed to replace this would be 1708 x 2.284 (see Appendix A) = 3901 litres of liquid hydrogen.

Direct electrical energy needed to produce 1 litre of liquid hydrogen = 4 kWh_e (as above).

So direct electrical energy needed to produce 3901 litres of liquid hydrogen = 3901 x 4 = 15,604 kWh_e.

In 2001 U.S. consumption of electricity amounted to about 3.5 x 10¹² kWh_e/yr.

So per capita consumption = 3.5 x 10¹² / 281 x 10⁶ = 12,455 kWh/yr.

So extra amount of electricity required for gasoline substitution, by hydrogen, = 15,604 / 12,455 = 1.25 times present amount.

{T4} U.S. natural gas *production* has roughly flat-lined for the last twenty years, at around 19 trillion cubic feet a year (tcf/yr). In the year 2000, US natural gas *consumption* was about 22 tcf. Between 1985 and 2000, imports from Canada increased by about 2.5 tcf/yr, to make up the difference. The increasing imports from Canada *might* just be because Canadian gas was cheaper, so U.S. gas producers consequently saw little profit in making substantial investment to expand production. However, that does not appear to be the explanation; rather it is increased difficulty in obtaining the gas: Texas, which produces one-third of US gas, in 1999 had to drill 6,400 wells to keep up its production, whereas 4,000 were sufficient in 1998. Neither are Canadian resources unlimited: Canadians are having to drill nearly 7,500 wells a year to keep up Alberta's production.

Another reason for doubting that U.S. natural gas supplies can be regarded as "abundant" is that the Energy Information Administration have suggested that by 2015 the US may need 50% more natural gas than today, i.e. another 11 tcf/yr. The Energy Administration did not say where this was to come from.

{T5} To make 1 t of gasoline requires 3.65 t coal, including the coal needed to carry out the conversion process (Durrant, 1953:309). I do not know whether the process has changed since the 1950s, but if not, it appears that nothing like all the carbon in the coal is released during the conversion process. For data passed to me by a reliable source, science journalist Bernard Gilland, was that burning gasoline releases 63 tC/TJ, while the hydrogenation process for converting coal to gasoline emits 48 tC/TJ, for a total of 111 tC/TJ. Thus synthetic gasoline releases 111 / 63 - 1 = 76% more carbon per unit of energy.

{T6} The American Wind Energy Association estimate that it would be possible to install sufficient wind turbines to produce 675 billion kWh/yr onshore plus a further 102 billion kWh/yr offshore, for a total 777 billion kWh/yr.

Assuming a capacity factor of 25% (this is probably optimistic: over two years, four northern European nations achieved a mean of 22%), this would require an installed capacity of of $777 \times 10^9 \times 1000 / (24 \times 365) / 0.25 = 354,794$ MW, say 355,000 turbines each of 1 MW capacity.

Because of short term unpredictability in the wind, it is unlikely that all of this would be used (UK data suggests a 14% loss), but ignoring that, and since U.S. electricity consumption was (in 2000) about 3.5 trillion kWh/yr, the 777 billion is 22% of the whole.

Over the final three decades of the last century, U.S. population growth was 1.06% per year. $1.0106^{20} - 1 = 23\%$, so 20 years of population growth would absorb the additional 22% output.

The capacity factor of conventional power stations is somewhat variable. A 70% figure for conventional power appears in Trainer (1995:1018), but more recently I have been coming across a 60% figure (which is quoted in the text).

{T7} Liquid hydrogen has a density of 0.070 kg/litre (McGraw-Hill, p. 338 of Vol.1, 8th edition). So 160 gms of hydrogen occupies $0.160 / 0.070 = 2.286$ litres.

{T8} The energy needed to make 1 litre of liquid hydrogen is 3.985 kWh_e (see endnote 3), so to make 2.286 would require $2.286 \times 3.985 = 9.11$ kWh_e. Note that if this electricity had to be made by burning fossil fuel, then the energy required would be $9.11 / 0.33 = 27.6$ kWh_{th}.

Note also that gasoline has an energy content of about 33.5 MJ/litre. Making the amount of hydrogen that has an equivalent motive power, namely 2.3 litre, would require $27.6 \times 3.6 \times 10^6 = 99.4$ MJ.

{T9} The pressure of 930 atmospheres, about 13,700 psi or 960 kg/cm², is calculated on the basis of hydrogen behaving like an ideal gas. In a real gas the pressure is likely to be higher.

References

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