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# No Alternative to Reality



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Published 06/30/2003

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The story has been around for decades and its recent recounting has been so frequent that everybody seems to know at least some bits of it. Its main ingredients are easy to list: of all known fuels only the combustion of hydrogen can produce nothing but the desirable heat and pure water; but it would be stupid to burn this unique fuel because the best way to use it is to feed it into fuel cells (FCs) where the element is combined (electrochemically) with oxygen to produce electricity and water; water goes harmlessly to the atmosphere (or into little papers cup from which it is drunk by green politicians and inventors trying to drum up financing for their cell companies) and the electricity can be used either for lighting and air conditioning in buildings or it could power electric motors to run road vehicles.

The entire process is inherently highly efficient and nonpolluting, and while it is true that the cost of FCs is still prohibitively high in comparison with the old-fashioned gasoline-burning internal combustion engines (ICEs), all that is needed is to start producing the cells in millions of copies and see the unit cost plummeting, much as it happened to microchips. This mass demand would naturally bring into existence the needed distribution networks for the lightest of all gases and we would all enjoy the nirvana of the hydrogen economy.

This story, favored for decades only by the sci-fi crowd and assorted technoenthusiasts, had first conquered most of the academic establishment and, during the past decade, it gained many corporate converts (particularly among the Japanese automakers).

**Hydrogen on the Horizon?**

Most recently it was embraced even by Midland's most famous oilman (but, to keep it in proper perspective, this was a very tentative conversion: $ 1.7 billion the Department of Energy committed to research on hydrogen cars over the next five years is less than half the money spent every year on just advertising for US cosmetics and toiletries). Have we thus reached the point of no return with the new world of hydrogen economy already discernible on the technical horizon? FCs promoters are convinced that this is indeed the case, and none too soon. After all, FCs, William Grove's old (1839) invention, saw their first practical use only during the early 1960s when NASA began installing small alkaline units on its spacecraft. This opened the way for thinking about terrestrial applications that would take advantage of cell's inherent advantages.

Even the cleanest ICEs produce CO2, the leading greenhouse gas: FCs emit no air pollutants. Rapid reciprocating movement of pistons puts hundreds of parts in ICEs under continuous stress and it produces noise; FCs have no moving parts, hence no mechanical stress and no noise. Thermodynamics limits the efficiency of heat engines to about 25% for the Otto cycle (gasoline motors) and 35% for diesels; in contrast, FCs have efficiencies on the order of 50% and even more than 70%. Gasoline has the highest energy density of all common fuels (double that of good bituminous coal, nearly triple that of wood) but liquid hydrogen's is 2.7 times higher, a great advantage in mobile applications.

And these advantages are only the technical half of the story: there would also be huge strategic and environmental gains. Hydrogen would make us eventually immune to the tightening global crude oil market. Its use would first lower and then eliminate rising Western dependence on oil imports. Hydrogen cars would do away with largely ICE-generated photochemical smog, now a near-constant presence and a health hazard in all large urban areas. And acrimonious debates about uncertain, but possibly catastrophic, impacts of rapid global warming would disappear as a hydrogen economy would emit no greenhouse gases.

And so we should be thankful to all those visionary minds that are busily constructing the hydrogen future. Half a dozen major FC designs are now under intensive, and accelerating, research and development in North America, Europe and Japan, all going under 3-5 letter acronyms: alkaline (AFC), proton exchange membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC), direct methanol (DMFC) and solid oxide (SOFC). Modular cell stacks with capacity up to 100 kW have been tested for electricity generation. And earlier this year Honda became the first automaker to offer its FCX, the first zero-emission FC car certified for everyday use. Not surprisingly, some forecasters see the initial phase of a truly massive diffusion of fuel cells installed in passenger cars taking place even before 2005 and that the transition from ICEs to FCs will be in full swing before 2010 and that the demise of ICEs may come just a decade later.

**Reality Intrudes**

Now for the reality. The only FC designs that have been successfully commercialized are AFCs in space and small capacity PAFCs for some types of stationary electricity generation, both representing important but relatively narrow-niche markets. While there are industrial hydrogen pipelines there is no infrastructure to distribute hydrogen to individual users while American motorists can buy gasoline at about 200,000 filling stations. This infrastructural void favors PEMFC-powered cars that would make it possible to use various hydrogen-rich liquids (methanol, even gasoline itself) rather than the pure gas itself --

but this may not be a good decision: if the hydrogen economy is really coming then it would be preferable to go directly to hydrogen cars. Not surprisingly, there is a large degree of uncertainty regarding the coming size of national and global fuel cell markets. Recent forecasts have differed by up to an order of magnitude and the divergence in projections has been actually increasing.

But even if some of the more optimistic forecasts were correct, one million US cars powered by fuel cells in 2010 would be less than 0.5% of all vehicles at that time. Going a step further to a full-blown hydrogen transport system would be a shift whose repercussions we cannot at this point fully comprehend.

At least one small benefit of the current interest in FCs is that even many scientifically illiterate enthusiasts now realize that *hydrogen is not an energy source, merely an energy carrier*. Unless we get some environmentally benign means of producing it by the electrolysis of water (that would require either exceedingly cheap photovoltaics or an entirely new generation of nuclear reactors) we would get it by using today's most practical method: steam reforming of natural gas. If you wonder how that would not lead to higher natural gas prices (and hence to higher oil prices as the two fuels are substitutable to a large degree) and how that would reduce our dependence on fossil fuels, you have to ask true hydrogen believers for an explanation.

Moreover, hydrogen is an inherently poor choice for a transportation fuel because its uniquely high energy density depends on its liquefaction, i.e. storage under high pressure, or at least on its incorporation into metal hydrides to avoid bulky fuel storage in vehicles. And here's a curiously underappreciated fact given the litigiousness of this society: what would be the liability repercussions of distributing a fuel that now can be handled only by select personnel to hundreds of thousand commercial outlets? For these, and other, reasons -- all of which have been detailed in some excellent technical reports that have called recently for rethinking hydrogen cars -- we are not on the threshold of a new era dominated by FCs and hydrogen.

**Techno-Economic Realities**

But there is yet another *fundamental consideration* whose understanding does not require any engineering or scientific expertise, merely an appreciation of long-term techno-economic realities.

Gasoline-fuelled ICEs have been around since the 1880s when Benz, Daimler and Maybach designed the first acceptable automotive versions. Rudolf Diesel's machines came a decade later. Their importance for smooth functioning of modern societies is taken entirely for granted in societies where their numbers match, and even surpass, the total numbers of population. The US population of about 285 million people now owns more than 210 million automotive and more than 100 million other internal combustion engines. The latter category includes more than 50 million engines in lawnmowers and other garden machines, about

17 million outboard and inboard engines in recreational boats, four million motorcycles and nearly two million snowmobiles. In addition, about 20 million small internal combustion engines, ranging from units for ultralight planes to emergency electricity generators, are now sold in the country every year.

Another key fact is that the aggregate installed power of ICEs is now considerably greater than that of any other prime mover. In the US the total capacity of vehicular ICEs is now more than 20 trillion watts compared to less than 900 billion watts installed in steam and water turbines, or more than a 20-fold difference. And a worldwide comparison shows that while in the year 2000 there were about 3.2 trillion watts installed in electricity-generating turbines, the global fleet of road vehicles alone had installed power of at least 60 trillion watts. Check all of these numbers once again, multiply them by the average cost of vehicles in which they are installed, add up the capital invested in the manufacturing facilities and in service infrastructure that has grown around gasoline and diesel-fuelled ICES -- and you will see that we have in place a system capitalized at at least $30 trillion, or roughly an equivalent of the world's annual gross economic product.

Systems of such magnitude are immensely inertial and, as rich historical experience confirms, can be replaced or radically restructured only after decades of gradual and relentless technical advances and infrastructural investment. So even if we already had much more competitive FCs we would not see the demise of ICEs in a decade or a in a generation: interestingly enough, the total number of draft animals in the US peaked in 1918, almost exactly 30 years *after* the commercial introduction of gasoline-fueled vehicles! And ICEs are no mules or horses: they can be made still much more efficient even after more than a century of advances.

The three most notable recent innovations are variable compression engines (VCE), homogeneous charge compression ignition (HCCI) and direct gasoline injection. While today's automotive gasoline-fuelled ICEs have their compression ratios fixed at around 9:1, in VCEs it can be changed continuously between 8:1 for heavy loads and as high as 14:1 for light duty. VCEs should reduce gasoline use by about 30% compared with equally powerful naturally aspirated machines. HCCI may eventually combine diesel efficiency (i.e. about 40% efficiency gain) with very low nitrogen oxide and particulate emissions. And direct gasoline injection can save about 20% of fuel while significantly reducing carbon dioxide emissions. And to commercialize these advances will need no new infrastructures, no multibillion dollar governmental subsidies, just persistent and relatively low-cost tinkering with the machine whose operation we understand better than that of any other mass-produced artifact.

Perhaps the easiest way to underscore the message is in the terms of familiar mpgs. Today's passenger cars (but not SUVs classified as light trucks) must fit into CAFE's minimum of 27.5 mpg. Better ICEs combined with lighter (but safer) and more aerodynamic car bodies and with smarter roads (computerized flow management, peak-traffic pricing) could, quite realistically, double that mean to 55 mpg within a decade -- with all of the attendant environmental gains. No new dramatic discoveries are needed to do that, no new infrastructures, no waiting for many years of cumulative performance of untried new techniques to pronounce them effective. Altogether a powerful argument for promoting better ICEs and an excellent foundation for concluding that these venerable machines are not going to be eliminated by hydrogen-powered FCs any time soon.

*Vaclav Smil does interdisciplinary research on many aspects of energy and the environment. His latest books are "The Earth's Biosphere" and "Energy at the Crossroads" (both with the MIT Press).*