Hydrogen lifts off — with a heavy load

The dream of clean, usable energy needs to reflect practical reality.

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Clean getaway? George Bush has proposed funding to develop hydrogen-fuelled vehicles.

For the energy-science community, the State of the Union address given by President George W. Bush this January contained a metaphorical hydrogen bomb. In a speech directed mainly at the woes of the US economy, the looming conflict with Iraq and the AIDS crisis in Africa, the president said: "Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car — producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

The White House later revealed the core programme to be a five-year, $720-million initiative dubbed 'FreedomFUEL'. It is aimed at developing technology to support a national infrastructure for hydrogen production and delivery, and is directed principally towards the replacement of petroleum as individual vehicular fuel. The Bush adminstration deserves much praise for championing US determination to pursue aggressively the realization of what is surely the ultimate 'clean' fuel. We will soon see if Congress agrees — as the old adage goes: "the President proposes, but the Congress disposes".

The key technology for hydrogen-driven cars and trucks will probably be fuel cells. These have been under development for many years, and are beginning to show some signs of reaching maturity in terms of cost and performance. So let us concede that the day finally comes when your newborn drives an economical fuel-cell-powered vehicle with enough on-board hydrogen storage to travel 500 km without having to refill at a hydro-station too often. Where will the hydrogen come from? After all, this is fuel you can't mine or drill for.

The White House's *FreedomFUEL Fact Sheet* gives only one clue: "Hydrogen can be produced from abundant domestic resources including natural gas, coal, biomass, and even water." Well, these resources will have to be staggeringly abundant. For hydrogen to supplant petroleum completely for transport, its production would require an enormous outlay in capital plant and a significant area of set-aside land. Even with a herculean effort on the model of the Apollo space programme, the hydrogen economy will arrive slowly, as it will require vast investment in infrastructure over a long period of time. This investment may not be driven by the market economy — it is more likely to evolve from a series of government energy-policy directives and legislative action that will mandate a blend of petroleum, methane, ethanol and hydrogen on the pathway to an eventual all-hydrogen transport supply. During this time there will certainly be a migration across several generations of technologies based on the internal-combustion engine, such as petroleum–electric hybrid vehicles.

Wasted opportunities

The United States uses almost 20 million barrels of petroleum every day, around 12 million of which power surface transport. A major portion of this is wasted, as internal-combustion engines have an efficiency of 20–30%. 'Only' three million barrels, therefore, are 'usefully' consumed. Because a fuel cell is not a heat engine, and theoretically at least, escapes the bottleneck of the second law of thermodynamics governing internal-combustion motors, only enough homemade hydrogen is needed to offset the energy content of these three million.

Future fuel cells may be able to convert about 80% of the Gibb's free energy released by combining hydrogen with oxygen to make water into electrical energy (at present, this factor is around 50%). Also included in this should be the losses in both electricity conversion and electric-motor efficiency, around 20%, to 'shaft energy' to move the car. Thus the overall efficiency is 64%, much better than can be obtained from gasoline or diesel engines. So, we would need to generate around 230,000 tonnes of hydrogen daily — enough in liquid form to fill 2,200 space-shuttle booster rockets or, as a gas, to lift a total of 13,000 Hindenburg airships. Hopefully the thirst for this enormous quantity could be quenched by a factor of two or three by employing more efficient aerodynamic and drive-train designs in future hydrogen vehicles. But then folks would probably drive that much more.

Hydrogen is not a 'primal' energy source. Unlike fossil fuels or uranium, more energy is used to extract hydrogen from its source than is recovered in its end use. For simplicity, and to bypass issues of carbon and carbon dioxide sequestration, let us assume that the hydrogen is obtained by 'splitting' water with electricity — electrolysis. Although this isn't the cheapest industrial approach to 'make' hydrogen, it illustrates the enormous production scale involved — about 400 gigawatts of continuously available electric power generation have to be added to the grid, nearly doubling the present US national average power capacity. The number of new power plants that would need to be built — based on presently available technologies — to meet this demand is roughly 800 natural-gas-fired combined-cycle units generating 500-megawatts, or 500 800-megawatt coal-fired units, 200 Hoover Dams (two gigawatts each), or 100 French-type nuclear clusters (four reactors, about one gigawatt each).

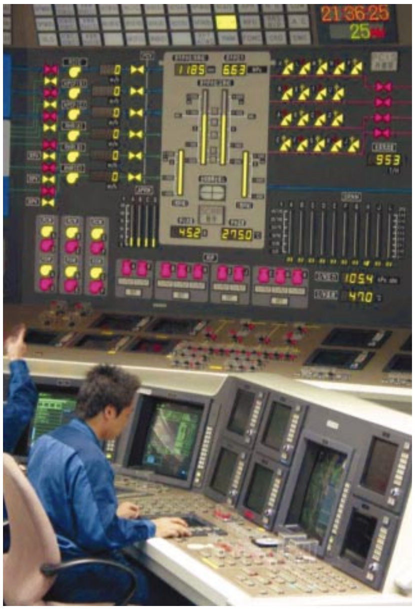
The average capital cost of building an electric power plant is $1,000 per kilowatt (with considerable variance), which would mean new investment of at least $400 billion (one-twentieth of US gross domestic product). This does not include the storage and delivery costs that would be incurred for a complete transformation to a surface-transport system running on hydrogen instead of petroleum. A daunting prospect, but not impossible. To get the daily hydrogen ration of 230,000 tonnes, just over two million tonnes of water is required. Even this vast amount of water expelled as 'exhaust' will be recycled to the environment in several days, unlike carbon dioxide.

A popular justification for moving from petroleum to hydrogen, one that is often invoked by US political pundits, is 'freedom from dependence on Middle East oil'. Yet according to the latest figures published by the US Energy Information Agency, only 14% of US oil imports come from Gulf states — Europe (30%) and Japan (75%) are much more reliant on these resources.

For me, the most compelling rationale for the hydrogen economy is the potential to drastically reduce carbon emissions. If we can get energy without oxidizing carbon, I believe it's a good idea to do it. According to studies by the Electric Power Research Institute in Palo Alto, California, about 97% of the hydrogen produced in the United States is derived from the thermocatalytic 'splitting' of natural gas or refinery gases, or 'coal gasification' — the reaction of water (steam) with carbon to yield hydrogen and carbon monoxide. The heat to effect both of these processes is based on fossil combustion. To derive hydrogen electrolytically for transport would therefore yield carbon emissions likely to offset most of the benefits of saving nine million barrels of petroleum per day.

Reality bites

What about using renewable energy resources for this job? Sweden's Norsk Hydro currently builds the largest electrolysers, and British Colombia-based firm BC Hydro recently completed a pilot project that is now making hydrogen for use in fuel-cell-powered buses in Vancouver. But I doubt whether we will see even one major new North American hydroplant built in the near (or far) future expressly to generate hydrogen, let alone 200 Hoover Dam equivalents.


KYODO

Nuclear know-how: the Kashiwazaki-Kariwa plant is a highly efficient new generation facility.

Wind and photovoltaic solar technologies are expected to approach power densities of about 10 and 100 watts per square metre, respectively, when the wind is blowing hardest and the Sun shining the brightest. Imposing a realistic annual duty factor of 20% on Sun and 30% on wind, the Earth surface area required to produce 400 gigawatts would be 130,000 km^2 for wind and 20,000 km^2 for solar technologies. The former is about the size of New York State, the latter about half the size of Denmark.

Another option, extracting energy from biomass through combustion, is attractive in principle, as the carbon emitted is recycled through future plant growth. About 15% of the land area in the United States is under cultivation, mostly for food. Some estimates put the annual biomass energy equivalent of these crops at roughly 23 million gigawatt-hours, or about 2,600 gigawatts of continuous power production[1]. To add an another 400 gigawatts of electrical power to produce hydrogen for transport would require another 3% to undergo cultivation, an area about the size of Nevada.

Whenever you do something 'massive' to ecology — such as pumping gigatonnes of carbon dioxide into the atmosphere, or proposing million-acre wind or solar farms — the environmental consequences are uncertain at best and disastrous at worst. An example that relates to carbon recovery or sequestration is the experiment that used iron to fertilize the oceans near Antartica in an attempt to capture carbon[2]. This resulted in huge algal blooms followed by emission of methyl bromide, an ozone poison.

If there is a way to make both electricity and hydrogen without releasing carbon dioxide, it would probably be wise to use it. In fact, it does exist and is already in use. I believe that its science is sound and solved, its technology mature and safe. It is called nuclear fission power. Its fuel costs are fixed and supply is assured for at least 500–1,000 years, by which time there may be neutron-free, 'clean' fusion — maybe. Readers accustomed to the unscientific belief that nuclear power is inherently dangerous and forever unsafe should examine the facts, starting with the article "The Need for Nuclear Power"[3]

Sensible solutions?

On the west coast of Japan, at Kashiwazaki Kariwa, the Tokyo Electric Power Corporation has spent 20 years building perhaps the world's most modern nuclear power complex. Its reactor units generate eight gigawatts of electric power, available 90% of the time, on a site that occupies slightly less than 4 km^2. The site includes a visitor centre, machine shops and on-site 'spent' fuel storage. More than a quarter of the plant area is green space. Sand dunes and native growth are left undisturbed. Yet the power density is still an amazing 1,800 watts per square metre. Thus, the 400 gigawatts of electricity needed to extract hydrogen from water to power US surface transport could be cumulatively generated on land occupying only 233 km^2.

Any form of highly concentrated potential energy, from dynamite to deuterium, will provide many opportunities for humans to misbehave and make mischief. Nonetheless, I believe that a resurgence of nuclear power is necessary for the continuing industrialization of world society with minimal environmental impact and eco-invasion, one in which hydrogen will supplant fossil sources. FreedomCAR and FreedomFUEL cannot be had without FreedomNUKES — and FreedomNUKES cannot be had in a world that continues to permit the unrestricted proliferation of nuclear weapons. International laws and institutions must be established to control and vigorously enforce the use of actinide materials for peaceful purposes from mine-head, through recovery and breeding, to eventual disposal, and to prevent diversion to rogue weapons programmes. Only then can the vision that the parents of the atomic age foresaw and desired be realized — a world where 'atoms for peace' would prevail, creating a clean energy source independent of any geographically accidental richness of fossil reserves. ■

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2. Boyd, P. W. *et al. Nature* **407,** 695–702 (2000).
3. Rhodes, R. & Beller D. *Foreign Affairs* **79,** 30 (2000).