Twenty Hydrogen Myths

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Supported by The Rose Family Foundation, The Harold Grinspoon Foundation, and New

ing opinions, and corrects twenty widespread misconceptions. It explains why the rapidly growing engagement of business, civil society, and government in devising and achieving a transition to a hydrogen economy is warranted and, if properly done, could yield important national and global benefits.

About the author

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About the publisher

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Hydrogen technologies are maturing. The world's existing hydrogen industry is starting to be recognized as big — producing one-fourth as much volume of gas each year as the global natural-gas industry. Industry, government, and civil society are becoming seriously engaged in designing a transition from refined petroleum products, natural gas, and electricity to hydrogen as the dominant way to carry, store, and deliver useful energy. New transitional paths are emerging, some with a vision across sectoral or disciplinary boundaries that makes them harder for specialists to grasp. Naturally, there's rising speculation about winners, losers, and hidden agendas. And as the novel hydrogen concept is overlain onto longstanding and rancorous debates about traditional energy policy, constituencies are realigning in unexpected ways.

In short, the customary wave of confusion is spreading across the country. What's this all about? Is hydrogen energy really a good idea? Is it just a way for incumbent industries to reinforce their dominance, or could it be a new, different, and hopeful melding of innovation with competition? Is it a panacea for humanity's energy predicament, or a misleading *deus ex machina* destined to inflict public disappointment and cynicism, or neither, or both?

The conversation about hydrogen is confused but hardly fanciful. The chairs of eight major oil and car companies have said the world is entering the oil endgame and the start of the Hydrogen Era. Royal Dutch/Shell's planning scenarios in 2001 envisaged a radical, China-led leapfrog to hydrogen (already underway): hydrogen would fuel a fourth of the vehicle fleet in the industrialized countries by 2025, when world oil use, stagnant meanwhile, would start to fall. President Bush's 2003 State of the Union message emphasized the commitment he'd announced a year earlier to develop hydrogen-fuel-cell cars (FreedomCAR).

Yet many diverse authors have lately criticized hydrogen energy, some severely.[1–12] Some call it a smokescreen to hide White House opposition to promptly raising car efficiency using conventional technology, or fear that working on hydrogen would divert effort from renewable energy sources. Some are skeptical of hydrogen because the President endorsed it, others because environmentalists did. Many wonder where the hydrogen will come from, and note that it's only as clean and abundant as the energy sources from which it's made. Most of the critiques reflect errors meriting a tutorial on basic hydrogen facts; hence this paper.

Introductory facts

To establish a common factual basis for exploring prevalent myths about hydrogen, let's start with six points that are universally accepted by hydrogen experts but not always articulated:

- Hydrogen makes up about 75% of the known universe, but is not an energy *source* like oil, coal, wind, or sun.[13] Rather, it is an energy *carrier* like electricity or gasoline — a way of transporting useful energy to users. Hydrogen is an especially versatile carrier be-

efficient.[20] (Both systems then incur further minor losses to drive the wheels.) This means you can drive several times as far on a gallon-equivalent (in energy content) of hydrogen in a fuel-cell car as on a gallon of gasoline in an engine-driven car. Conversely, hydrogen costing several times as much as gasoline per unit of *energy contained* can thus cost the same *per mile* driven. Since you buy automotive fuel to get miles, not energy, ignoring such differences in end-use efficiency is a serious distortion, and accounts for much of the misinformation being published about hydrogen's high cost. Hydrogen's advantage in cars is especially large because cars run mainly at low loads, where fuel cells are most efficient and engines are least efficient.[21] (Hydrogen can also have other economic or functional advantages that go beyond its efficient use. For example, when hydrogen fuel cells power digital loads in buildings, hydrogen may yield even greater extra value because suitably designed arrays of fuel cells can be exceptionally reliable and can yield the high-quality power that computers need.[22])

To reinforce this sixth point, the U.S. Department of Energy (DOE) says bulk hydrogen

- RMI’s insights into the full economic value of distributed power suggest that hydrogen fuel cells *today* can economically displace less efficient central resources for delivering electricity, paving the way for hydrogen use to spread rapidly, financed by its own revenues.
- RMI recognizes that especially in North America, natural gas is logically the main near-term fuel to launch the hydrogen transition, along with cost-effective renewables. If making hydrogen requires more natural gas (which it may not — see Myth #12), it should come first from natural gas saved by making existing applications more efficient. In the longer run, more mature and diverse renewables will play an important and ultimately a dominant role. Even during the initial, mainly fossil-fueled, stages of the hydrogen transition, carbon emissions will be much smaller than today’s emissions from burning those fossil fuels directly. In time, those carbon emissions will approach zero. Insisting that they *start* at zero — that hydrogen be made solely from renewable energy sources, starting now — is making the perfect the enemy of the good. But done right, the hydrogen transition will actually make renewable energy more competitive and speed its adoption.

And what “headlines” will emerge from this perspective in the following discussion?

- **The oft-described technical obstacles to a hydrogen economy —!storage, safety, and the cost of the hydrogen and its distribution infrastructure —!have already been sufficiently resolved to support rapid deployment starting now. No technological breakthroughs are needed, although many will probably continue to occur. Until volume manufacturing of fuel cells starts in the next few years, even costly hand-made or pilot-produced versions can already compete in substantial entry markets. Automotive use of fuel cells can flourish many years sooner if automakers adopt recent advances in crashworthy, cost-competitive ultralight autobodies. If fuel cells prove difficult to commercialize or hydrogen’s benefits are desired sooner, there might even be a transitional role for hydrogen-fueled engine-hybrid vehicles.**
- **The hydrogen transition should not need enormous investments in addition to those that the energy industries are already making. Instead, it will displace many of those investments. Hydrogen deployment may well need net capital than business-as-usual, and should be largely self-financing from its revenues.**
- **A well-designed hydrogen transition will also use little more, no more, or quite possibly natural gas than business-as-usual.**
- **A rapid hydrogen transition will probably be profitable than business-as-usual for oil and car companies, and can quickly differentiate the business performance of early adopters.**
- **Most of the hydrogen needed to displace the world’s gasoline is already being produced for other purposes, including making gasoline. A hydrogen industry big enough to displace all gasoline, while sustaining the other industrial processes that now use hydrogen, would be only severalfold bigger than the mature hydrogen industry that exists today, although initially it will probably rely mainly on smaller units of production, nearer to their customers, to avoid big distribution costs.**
- **A poorly designed hydrogen transition could cause environmental problems, but a well-designed one can resolve most of the environmental problems of the current fossil-fuel system without making new ones, and can greatly enhance security.**

ergy, net of compressor consumption[32] — thus enabling hydrogen's more efficient end-use to de-

reduced by 15% because of the way hydrogen's energy content is normally measured.[46]) So why incur these losses to make hydrogen? Because hydrogen's greater end-use efficiency can more than offset the conversion losses, much as an electric heat pump or air conditioner can offset fuel-to-electricity conversion losses by using one unit of electricity to concentrate and deliver several units of heat. That is, conversion losses and costs are tolerable if the resulting form of energy is more efficiently or conveniently usable than the original form, hence justified by its greater economic *value*. Making hydrogen can readily achieve this goal.

Crude oil can be more efficiently converted into delivered gasoline than can natural gas into delivered hydrogen.[12] But that's a red herring: the difference is far more than offset by the hydrogen's 2–3-fold higher efficiency in running a fuel-cell car than gasoline's in running an engine-driven car. Using Japanese round numbers from Toyota, 88% of oil at the wellhead ends up as gasoline in your tank, and then 16% of that gasoline energy reaches the wheels of your typical modern car, so the well-to-wheels efficiency is 14%. A gasoline-fueled hybrid-electric car like the 2002 Toyota *Prius* nearly doubles the gasoline-to-wheels efficiency from 16% to 30% and the overall well-to-wheels efficiency from 14% to 26%. But locally reforming natural gas can deliver 70% of the gas's wellhead energy into the car's compressed-hydrogen tank. That "meager" conversion efficiency is then more than offset by an advanced fuel-cell drivesystem's superior 60% efficiency in converting that hydrogen energy into traction, for an overall well-to-wheels efficiency of 42%. That's three times higher than the normal gasoline-engine car's, or 1.5 times higher than the gasoline-hybrid-electric car's.[47] This helps explain why most automakers see today's gasoline-hybrid cars as a stepping-stone to their ultimate goal — direct-hydrogen fuel-cell cars.

In competitive electricity markets, it may even make good economic sense to use hydrogen as an electricity storage medium. True, the overall round-trip efficiency of using electricity to split water, making hydrogen, storing it, and then converting it back into electricity in a fuel cell is relatively low at about 45% (after 25% electrolyzer losses and 40% fuel-cell losses) plus any by-product heat recaptured from both units for space-conditioning or water heating. But this can still be worthwhile because it uses power from an efficient baseload plant (perhaps even a combined-cycle plant converting 50–60% of its fuel to electricity) to displace a very inefficient peaking power plant (a simple-cycle gas turbine or engine-generator, often only 15–20% efficient).

This peak-shaving value is reflected in the marketplace. When the cost of peak power for the top 50–150 hours a year is $600–900/MWh, typically 30–40 times the cost of baseload power (~$20/MWh), the economics of storage become quite interesting. Distributed generation provides not only energy and peak capacity, but also ancillary services and deferral of grid upgrades. Hydrogen storage can also save power-plant fuel by permitting more flexible operation of the utility system with fuller utili 12.24 780.06 cm BT 50 0 0 ,ven a combi7w0thiefereoo flexible operation of the utility

Many people assume that fuel makes more electricity if burned in an efficient power plant than if

authorities, who have licensed 5,000-psi (~350-bar) hydrogen tanks, are expected to follow suit shortly. Linde AG recently installed a 700-bar German filling station for Adam Opel AG.[78]

Such carbon-fiber tanks could be mass-produced for just a few hundred dollars, and at the currently U.S.-approved safety factor of 2.25, they can hold ~11–12% hydrogen by mass. A 350-bar hydrogen tank (2.7 MJ/L at LHV and 300 K) is nearly ten times the size of a gasoline tank for the same energy content. However, the 2–3-fold efficiency advantage of the fuel cell, *i.e.*, less energy expended per mile, compared to a gasoline engine reduces this enlargement to ~3.2–4.8-fold — even less when you include the saved size and weight of other parts of the car that are no longer needed, such as the catalytic converter.

Technically, Hypercar vehicles are ultralight, ultra-low-drag, hybrid-electric vehicles with highly integrated and radically simplified design emphasizing software-driven functionality. The basic attributes of Hypercar, Inc.'s *Revolution* concept vehicle, simulated using sophisticated industry-standard design tools, include:

- Comfortably seats 5 adults; 69 ft^3 / 1.96 m^3 cargo with rear seats folded flat; flexible interior packaging
- 99 mpg-equivalent (EPA 115 city, 84 highway) (2.38 L/100 km, 42 km/L) with compressed H_2 running a 35-kW_e fuel cell buffered by 35 kW_e of NiMH storage — 5

pander like a supercharger run backwards. In addition, where the compressor's externally rejected heat can be put to good use, it need not be wasted. And compression energy is logarithmic — it takes about the same amount of energy to compress from 10 to 100 bar as from 1 to 10 bar, so using a 700- instead of a 350-bar tank adds only ~1–2 percentage points to the energy consumption, raising the compression energy from ~9–12% to ~10–13%. Modern electrolyzers are therefore often designed to produce 30-bar hydrogen, and some electrolyzers in advanced development yield 200 bar, at only a slight efficiency penalty. This can cut the compression energy required for filling a 350-bar tank by half or by three-fourths, respectively[83] — *i.e.*, to only plants' fuel and efficiency), would be small and temporary enough to create little electrical load or climatic concern before their electricity source was switched to renewable energy technologies.

a. Hydrogen pure enough for fuel cells would cost ~$15–22/kg.

Some analysts state, as does the Department of Energy's hydrogen program plan,[12] that "Fuel cells require hydrogen that is 99.999% pure, which today costs about $15 to $22 per kilogram" based on an assumed cost of about $450,000 per 60 kg/d reformer (enough for about 12 rather inefficient cars) — a cost DOE wanted to halve by 2010. However, in mid-2003, DOE drafted a new and realistic goal of delivering $1.50/kg hydrogen to cars by 2010.[94] This dramatic decrease is due partly to the realization that five-nines purity isn't necessary — even though technological innovators are increasingly reporting encouraging results with solid membranes (such as palladium-copper alloys) that can yield five-nines hydrogen at acceptable cost. A 112 kg/d (2,000 scf/h) reformer from H_2Gen, serving 20 garden-variety fuel-cell vehicles per day with perfectly adequate 99.99%-pure hydrogen at 476 bar, is expected at modest production volumes to compete with wholesale gasoline, *i.e.*, at a hydrogen price roughly *one-tenth* of DOE's original target. Such reformers are expected to enter the market from several manufacturers long before 2010. Some authoritative sources consider 99.9% purity adequate for typical automotive fuel cells;[95] Japanese automakers typically design to their national industrial standard of only ~98.5% purity.

Myth #10. We'd need to lace the country with ubiquitous hydrogen production, distribution, and delivery infrastructure before we could sell the first hydrogen car, but that's impractical and far too costly — probably hundreds of billions of dollars.

RMI's hydrogen strategy,[52] summarized in an earlier sidebar (Myth #4), shows how to build up hydrogen supply and demand profitably at each step, starting now, by interlinking deployment of fuel cells in buildings and in hydrogen-ready vehicles, so each helps the other happen faster. Such linkage, introduced by RMI in 1999, was adopted in November 2001 by the U.S. Department of Energy[12] and is part of the business strategy of GM,[96] Shell,[97] and other major auto and energy companies.

Extensive studies by the main analyst for Ford Motor Company's hydrogen program indicates that a hydrogen fueling infrastructure based on miniature natural-gas reformers, including sustaining their natural-gas supply, will cost about $600 per car *less* than sustaining the existing gasoline fueling infrastructure, thus saving about $1 trillion worldwide over the next 40 years.[53] Thus, far from being too costly, a switch to hydrogen could well cost less than what we already do — largely because the needed investments tend to be smaller for gas than for oil, by an amount sufficient to pay for reforming natural gas into hydrogen and delivering the hydrogen into cars. In absolute terms, a filling-station-sized natural-gas reformer, compressor, and delivery equipment would cost about $2–4 billion to install in an adequate fraction (10–20%) of the nation's nearly 180,000 filling stations.[98] Even a small (20 car/day) reformer would cost only about a tenth as much as a modern gasoline filling station costs (about $1.5 million,[3] not counting the roughly threefold larger investment to produce and deliver the gasoline to its tanks — a far more capital-intensive enterprise than producing and delivering natural gas to a reformer at the same

but temporary use for nuclear plants as long as they are allowed and economical to operate. (That will be until the next big accident or sabotage incident, or repairs become too costly, or the regulatory system becomes politically accountable, or historic exemption from major-accident liability is removed — whichever comes first.) However, since electricity is fungible and nuclear plants are generally dispatched whenever available, any nuclear electricity used to make hydrogen would normally result in the displacement of that baseload generation into the increased operation of existing coal-fired plants, thus reversing any climate benefits from using the hydrogen. And, of course, nuclear power is not the only major way to expand U.S. electricity generation, let alone the fastest or cheapest way. U.S. installed nuclear power capacity now produces less total electricity than could cost-effectively come, for example, just from the ~400 GW of high-grade windpower potential on Tribal lands in the Dakotas.[107]

Long-term, large-scale choices for making hydrogen are not limited to costly renewables-or-nuclear electrolysis *vs.* carbon-releasing natural-gas reforming:

- Reformers[10] can use a wide range of biomass feedstocks which, if sustainably grown, don’t harm the climate. Some can actually help the climate, such as reforming methane from anerobic digestion of manure that would otherwise release methane (a greenhouse gas 23 times more potent per molecule than CO over a 100-year horizon) into the air. In some cases, it may also make sense to gasify municipal wastes to make hydrogen.
- With biomass, waste, and fossil-fuel feedstocks, reformers can also be coupled with carbon sequestration. Since 1996, Statoil ASA, Norway’s state oil company, has been reforming natural gas from a North Sea field and reinjecting 1 MT/y of separated CO_2 into the reservoir (also a common method of enhanced oil recovery). This promising method can yield three profit streams — from hydrogen, enhanced hydrocarbon recovery, and carbon sequestration. However, it is centralized and hence incurs hydrogen delivery costs.
- Another Norwegian firm, Aker Kværner Group ASA, is scaling up a plasma-arc process that separates hydrocarbons (typically natural gas or oil) into 48 mass percent hydrogen, 10% steam, and 40% carbon black, which can be used (for tiremaking, metallurgy, etc.) or simply stored in an inert or reducing atmosphere. No CO_2 is released, so this process, operating since 1992, can also be a backstop in case basic problems emerge with carbon sequestration.[109]
- Some experimental methods of sequestration, notably those that capture the carbon in blocks of artificial rock without requiring extra energy (the reaction releases rather than requires heat), may be capable of scaling down to serve decentralized reformers.

Nor is it generally true that electricity from renewable sources is uncompetitively costly, leaving no climate-safe source to run electrolysis except nuclear power. Florida Power & Light now sells the output of its 100-MW windfarms for 2.5¢/kWh (net of the 1.7¢/kWh production tax credit meant to offset the larger subsidies to fossil and nuclear power). That unsubsidized ~4.2¢/kWh busbar price is the cheapest new bulk power source known, emits no carbon, and is driving the 30–40%/y expansion of global windpower, which exceeded 31 billion watts by the end of 2002. Windpower has lately added more than twice the global capacity each year that nuclear power did in the 1990s.[110] Europe plans to get 22% of its electricity from renewable sources by 2010 — 2.4 times the 2002 U.S. fraction or the official 2010 U.S. forecast — and is investing €2.12

location is regrettably proposed in the President's 2004 budget, which seems to take hydrogen funds mainly out of efficiency and renewables.[117] But both many renewables *and* many hydrogen programs are worthwhile and important for national prosperity and security, they support each other, and their diversity is inherently valuable, so we should do both, not sacrifice one for the other. Trading them off would be a sign of uninformed and therefore poor policy, not a demerit of hydrogen.

Hydrogen funds can be misspent. DOE has long been setting hydrogen goals that were already met; some encouraging signs are emerging that it may be starting to break this habit. FreedomCAR could be a triumph or a bust for U.S. automaking, depending on how well it's executed; one can't yet tell which it'll be.[118] But again, the remedy for poor program design is to improve it, not to reject the whole concept. Happily, most of the investment in hydrogen, done right, will come from profit-seeking private-sector investments, not from tax dollars.

Hydrogen particularly favors clean, safe power sources over dirty, dangerous, and proliferative ones by creating two major new advantages for renewable sources of electricity:

- The 2–3-fold more efficient use of hydrogen than gasoline in the car means that at the wheels, the equivalent of $1.25/gallon ($0.33/liter) U.S. retail gasoline is electricity at about 9–14¢/kWh with a proton attached to each electron. Since electricity sells for only about 2¢/kWh in competitive U.S. wholesale markets, the proprietor of, say, a hydroelectric dam or windfarm can get a 4–8-fold better price (even more in higher-priced countries) by turning a raw commodity (electrons) into a value-added product (hydrogen) in the notion that all hydrogen must come solely from renewable energy in the near term, they will only ensure our continued and growing dependence on foreign oil."[123] That is, if fossil fuels, chiefly natural gas, are responsibly obtained and safely delivered, then temporarily using them to launch the hydrogen transition (even with modest carbon releases), until their carbon is sequestered or they are replaced by renewables, is far better than the status quo — bigger carbon releases and little progress on hydrogen. It is also far better for renewables than turning hydrogen-from potentially a great accelerator of renewables into a hostage to their short-term competitiveness in hydrogen-making applications, which are typically more challenging than traditional direct uses for renewable energy sources.

c. Switching from gasoline to hydrogen will worsen climate change unless we do a large amount of successful carbon sequestration.

This might occur if we were naïve enough to burn coal in central power plants to make electricity to split water.[124] However, as explained above, that way of making hydrogen is clearly uneconomic even in existing coal-fired plants, which generally cost about 2–4¢/kWh to operate, plus an average of nearly 3¢/kWh to deliver the electricity to customers, or more to deliver centrally electrolyzed hydrogen. Reforming natural gas is far cheaper at any plausible price.

As mentioned in Myth #4, decentralized reformers do release CO_2, but no more than half as much as now comes out your tailpipe, and plausibly 3–6 times less depending on how efficient the fuel-cell car is (assuming the same hydrogen content in the feed material). Until we internalize carbon costs, or natural gas becomes far costlier, or (most likely) renewable electricity gets cheaper, that's a good first step. Once any of those things happens, renewable electricity, or wellhead-reformed natural gas or oil with carbon sequestration, will gradually take over, and the hydrogen system's carbon emissions will head towards zero. This conclusion is clearest with, but does not depend on, a transition to renewable sources. As Princeton University's Carbon Mitigation Initiative has found, "if H_2 vehicles can be made competitive when the H_2 is produced from fossil fuels with CO_2 vented [as this paper argues], those vehicles would probably also be competitive with the CO_2 captured and stored."[125]

Illustrative numbers: a ~70–80%-efficient reformer feeding a ~50–70%-efficient fuel cell, both onsite, yields a combined efficiency, from retail natural gas to electricity, of ~35–56%, minus a few percent for gas compressor losses if not recovered, plus any recovered onsite byproduct heat that displaces fuels. Using natural gas instead to make electricity, net of grid losses, is about 49–54% efficient using a combined-cycle plant, or <20–30% using simple-cycle turbines or classical condensing power plants. But none of these choices offers the customer as good options for byproduct heat recovery as onsite hydrogen appliances and fuel cells do, so after doing that, the fuel-cell system can be anywhere from slightly more to far more efficient in avoiding fuel use and CO_2 emissions. (The CO_2 advantage might shift if cost-effective ways were developed to sequester carbon from centralized but not from distributed uses.)

d. Making hydrogen from natural gas would quickly deplete our gas reserves.

Natural gas is at least a 200-year global resource, has only about half the carbon content per unit energy of oil, is far more widely distributed than oil (including major gas reserves in North

- increasingly, traders will buy avoided externalities such as NO_x and CO_2 emissions.[132]

The hydrogen in hydrocarbons is generally worth more without the carbon than with the carbon: that is, hydrogen plus “negacarbon” — carbon that Kyoto traders will pay you not to emit — is typically worth more than hydrocarbon. But surprisingly, this conclusion may not depend on whether avoided carbon emissions are valued much or at all. For example, gasoline is sold to

(depending on whether the carbon from the reformer is sequestered), while hydrogen from electrolysis releases no CO_2 when using climate-safe electricity.

c. Using hydrogen would dry out the Earth by leaking hydrogen to outer space.

Taking the opposite tack, one imaginative correspondent initially suggested a "fatal flaw in the hydrogen economy": a *reduction* in the planet's water inventory, because molecular hydrogen will inevitably be lost to outer space as hydrogen leaks (to an extent that he expects to exceed the claimed 5–10% loss of natural gas) or is incompletely combusted.[140] But this does not seem a realistic concern, because, as that author now accepts:

- Molecular hydrogen is reactive enough that all but about 0.04% of its current additions to the atmosphere (which total roughly 0.5% of the atmospheric inventory, or a million tons a year, nearly all from human activities) recombines chemically within the atmosphere, rather than escaping to outer space.[141]
- As is routinely done in today's large hydrogen industry, hydrogen leaks will be kept very small for both economic and safety reasons — smaller than current natural-gas leaks, which worldwide are around 1% and falling, but in well-run systems in industrial countries are around 0.1–0.5%.[142] For example, in Germany in the mid-1990s, the natural-gas system leaked 0.7%, but the hydrogen system leaked only 0.1%:[143] precisely because hydrogen escapes more easily, the hydrogen industry avoids leak-prone compression and threaded fittings commonly used for natural gas.
- Switching from today's fossil-fuel economy to an all-hydrogen economy with a 1% leakage rate would release about as much molecular hydrogen as is now released by fossil-fuel combustion, so as a first approximation, nothing would change.[144]
- For economic reasons, most hydrogen will long be made from fossil fuel, so all of it (or half of it if steam-reformed) will come out of the ground, not out of the contemporary atmosphere.
- Our planet's water supply is also being continually topped up. Every few seconds, small comets drizzle a house-sized, ~20-40 ton lump of snow into the upper atmosphere.[145] This mechanism, adding about an inch of water to the Earth's surface every 20,000 years, is enough to account for the planetary ocean. It would exceed by at least hundreds of times any plausible water loss from even a very large and leaky hydrogen economy.[146]

d. Using hydrogen would harm the ozone layer or the climate by leaking too much water-forming and chemically reactive molecular hydrogen into the upper atmosphere.

A final climate-/atmospheric-science myth was instantly created and intensively publicized worldwide after the respected journal *Science* embarrassingly published in June 2003 a paper that should not have passed peer review.[147] *CNN Headline News*, for example, aired half-hourly reports of the "dark cloud" of environmental risk just discovered to be hanging over those supposedly clean hydrogen fuel-cell cars. The *Science* paper projected that molecular hydrogen releases into the atmosphere could be ~4–8-fold higher in a hydrogen economy than in today's fossil-fuel economy, and that this could cause a variety of problems with climatic stability and the protective ozone layer in the stratosphere, ranging from hydroxyl-radical chemistry to stratospheric cloud formation and disturbance of high-altitude photochemistry. Assuming that the

CalTech authors' climate science and treatment of the fate of released hydrogen are correct (both are in some dispute), their whole argument is nonetheless invalid because they assume a 10–20% hydrogen leakage rate, which is about 10–400 times too high. If the leakage rate were in fact 10–20% from today's 50 MT/y hydrogen production, then the total hydrogen releases caused by human activity, which the authors say are 15±10 MT/y — all previously believed to come from incomplete combustion and methane emissions of fossil fuels and biomass — would instead be roughly one-third to two-thirds due to leaks of industrial hydrogen. No such source term has use of renewable energy without going through hydrogen would of course displace fossil fuels without any hydrogen leaks.)

Altogether, these factors would make a soundly designed hydrogen economy *reduce* current releases of hydrogen by one or perhaps two orders of magnitude, to a level well below natural hydrogen releases.[153] Thanks to the authors' and journal's carelessness, much research will now be done to ensure this outcome, which was highly likely anyhow, and many hydrogen advocates will spend as much time debunking this new myth as they already spend rebutting older ones like the *Hindenburg* (Myth #2).

Myth #15. There are more attractive ways to provide sustainable mobility than adopting hydrogen.

In general, the best way to get access to where you want to be is to be there already, via sensible land-use (spatial planning or its market equivalent — American communities would have a lot less sprawl if their governments at all levels didn't mandate and subsidize it). The next best way is "virtual mobility" — move just the electrons and leave the heavy nuclei at home. The third best way is to have real competition, at honest prices, between all modes of travel and of not needing it. For physical mobility, hydrogen offers distinctive environmental, security, and (if done right) economic advantages, but these advantages should supplement, not supplant, an integrated policy framework for equitable access.

a. We should run cars on natural gas, not hydrogen.

Some authors say it's cheaper and better to fuel a car engine with compressed natural gas than to carry the natural gas aboard the car, reform it into hydrogen onboard, and feed it into a fuel cell. That may be true, at least until fuel cells become quite inexpensive. But it's generally not true when you take the reformer out of the car, where it has an asset utilization around 0.6%, and put it in a filling station where it can be highly utilized and needn't be carried around. In other words, if you're powering a car with fuel cells, you should carry only the hydrogen aboard, using safe modern tanks (Myth #7), not a hydrocarbon fuel and a reformer to process it into hydrogen.

Cars fueled with compressed natural gas or LPG have become quite popular in fleet markets and with some customers (especially government fleets, which must meet an alternative-fuels mandate) and in some countries (such as India and China, where conversions are cutting urban air pollution). They usually lower fuel and maintenance costs significantly and cut smog, but don't compromise safety. It's reasonable to suppose that hydrogen fuel cells, which provide all these advantages to an even greater degree, should win even more market support.

b. We should convert existing cars to carry both gasoline and hydrogen, burning both in their existing internal-combustion engines, to create an early hydrogen market and reduce oil dependence and urban air pollution.

A hydrogen-optimized internal-combustion engine can be ~30–50% more efficient than today's gasoline engines — *i.e.,* about as efficient as a diesel engine, but much cleaner. BMW even hopes to raise the peak fuel-to-output-shaft efficiency of new hydrogen internal-combustion engines to ~50%. Converting existing cars to hydrogen fueling, however, would capture a much smaller efficiency gain. Enthusiasts of such fuel-system retrofits have not convincingly explained how an internal-combustion-engine car could get a decent driving range from the hydrogen without using such a big hydrogen tank as to leave insufficient space for people and cargo. If the idea is to use gasoline for range and hydrogen for city-center driving (where clean air is more valuable), it's probably cheaper and easier to scrap the dirty old cars and replace them with superefficient ones, such as existing hybrids that also have ultra-low emissions running just on gasoline. The early hydrogen market can best be created not in dual-fueled cars, which could give hydrogen a reputation for short driving range, but rather in buildings. There, ultra-reliable and digital-quality fuel-cell power, the reuse of "waste" heat for heating and cooling, and competing with delivered electricity (a very costly form of energy[154]) can make even today's costly handmade fuel cells cost-effective today if properly sited and used.[155] Hydrogen will be better accepted if hydrogen vehicles are uncompromised from the start.

However, it may be possible to provide tolerable interim results with a hydrogen-fueled internal-combustion-engine *hybrid* car by combining the efficiency gains of the hydrogen fueling with those of the hybrid-electric powertrain, as in Ford's 2003 "Model U."[156] That concept car is nearly 1.7× more efficient than its gasoline-fueled base model, with less than half the improvement coming from greater engine efficiency. Its 700-bar H_2 tanks are >4× bulkier than a same-batteries." Although batteries' energy density, life, and cost can be considerably improved, it is still probably easier to make a good fuel cell than a good battery, and the comparative advantage of the technologies that compete with batteries is probably more likely to expand than to shrink.

Regulators that, like the California Air Resources Board, have rewarded automakers for increasing the "zero-emission range" (battery capacity) of their hybrids are distorting car design in an undesirable direction, increasing the car's weight and cost in a way that doesn't well serve their strategic policy goals. However, such recent CARB concepts as requiring hybrids to have at least 8 kW of electric drive capacity and at least 60-volt traction motors are helpful, because they'll force real hybrid technology, rather than rewarding just a routine shift to 42-volt electrical systems that permit the starter/alternator to provide a minor torque supplement.

d. If we have superefficient vehicles, we should just run them on gasoline engines or engine-hybrids and not worry about hydrogen or fuel cells.

It would indeed be feasible and attractive to put an internal-combustion engine or hybrid-electric powertrain, fueled by gasoline or compressed natural gas or LPG, into an ultralight, ultra-low-drag autobody. Transplanting a Honda *Insight*'s 1-liter gasoline engine and 10-kW electric "assist" motor into a 3η SUV (*i.e.*, one with tripled platform-physics efficiency like the *Revolution* concept car[163]) would make quite an attractive vehicle, getting perhaps ~70 mpg (author's estimate, not a formal simulation result) instead of ~100. However, once we do have such vehicles — nominally 3η if engine-driven, 4η if engine-hybrid-driven, 5η if fuel-cell-powered — on the road, *whatever* their fuel and powertrain, they will make *all* powertrains far cheaper by making them three times smaller and probably simpler. Which powertrains will then compete best when all become smaller? I think such competition will ultimately tend to favor fuel cells, because they scale down better, being inherently modular and probably having less fixed-cost "overhead" than engine-driven powertrains, with or without hybrid drive. Fuel cells also undoubtedly have more potential for maturation and simplification, and lower asymptotic costs at very high volume, than the internal-combustion engine, now highly mature after about a century of volume production. In the short term, scaled-down hybrids can offer excellent solutions for efficient platforms. But hybrids are not merely competitors to fuel cells; they will also pave the way for them by bringing all the other elements of electric traction, such as motors, power electronics, and buffer storage devices, to mature, high-volume, low-cost production. This will enable fuel cells to compete on their own merits as they too become cheaper, without being held back by ancillary system costs; and they will not suffer from the duplicative and complex systems used by most hybrids.

To see how integrative, superefficient vehicle design can accelerate hydrogen deployment, just reverse the logic. If we *don't* have 3–5η vehicles, we'll need fuel cells three times as big per car, requiring many more years of selling large numbers of fuel cells at a loss (or into niche markets) before production volumes bring down the cost enough to compete in cars. If we *do* have 3η platforms (ultralight, ultra-low-drag, highly integrated design), they will greatly accelerate market capture by hydrogen fuel cells and hence displacement of oil, which more and more people think would be a good idea and may be very profitable.[164] Even if hydrogen and fuel cells *didn't* prove attractive, therefore, 3η platforms could still yield enormous oil-saving benefits for national security, economic prosperity, and the environment. It appears, therefore, that the hydrogen economy needs superefficient vehicles a lot more than superefficient vehicles need the hydrogen economy.

Myth #16. Because the U.S. car fleet takes roughly 14 years to turn over, little can be done to change car technology in the short term.

Gasoline-engine hybrid-electric cars, with about 150,000 on the road worldwide, currently command less than 1% of the U.S. car market, though far more in some localities. A fuel-frugal car (the two-seat Honda *Insight* can drive from Washington DC to Chicago on one 11-gallon tank of gasoline) looks even better in troubled times with spiking gasoline prices. But we needn't wait for normal fleet turnover to bring in such innovations, let alone fuel-cell cars. There is a large portfolio of policy options to accelerate fleet turnover. Perhaps the most attractive approach would be "feebates": buying a new car incurs a fee or earns a rebate, depending on its efficiency. The fees pay for the rebates. Ideally, the rebate for buying an efficient new car depends on the *difference* in efficiency between the new car you buy and the old car you scrap. The bounty received for scrapping a clunker could be unbundled from the new-car purchase, rewarding also the car owners who scrap but don't replace; either way, the government would offer you more for your gas-guzzler than you'd get for a normal trade-in because the clunker is worth more to society dead than alive. Detroit could also sell more cars, replacing the least efficient (and often dirtiest) ones prematurely scrapped — and yielding disproportionately big and fast benefits for air, oil, climate, jobs, and national security.

Feebates are not a new concept — the California legislature approved such a "Drive+" system by 7:1 in 1990, only to see it pocket-vetoed by Governor Deukmejian. Scrappage isn't novel either: both Unocal and the California Air Resources Board pay to get the most polluting cars off the road. Combining these two options holds promise of a win-win political outcome while greatly accelerating the turnover of the car stock; likewise for heavy vehicles and even more so for aircraft.liki4PC woreE-50 448mfhe tuov1mmeavye U.Srot benefits for

Myth #17. A viable hydrogen transition would take 30–50 years or more to complete, and hardly anything worthwhile could be done sooner than 20 years.

Under development since 1991, 3–5η

transition that bootstraps its investment from its own revenue and earns an attractive return at each stage.[52]

Myth #19. A crash program to switch to hydrogen is the only realistic way to get off oil.

Hydrogen can be a very important ingredient in getting off oil, but is less important than end-use efficiency and is best combined with it. Without efficient cars (ultralight, low-drag), fuel-cell adoption will be unnecessarily slow and costly. An RMI analysis for Royal Dutch/Shell Group Planning in 1987–88 found a technical potential to save four-fifths of U.S. oil through more efficient use (and direct substitution of saved natural gas) at an average cost below $4/barrel in 2003 dollars. Today's potential is even larger and cheaper, and RMI is updating that analysis. Integrating potential substitutions by hydrogen and biofuels will probably yield a potential to save far more oil than we use, at lower cost than we pay, and sooner than almost anyone now thinks possible. Watch for RMI's major analysis *Out of the Oil Box: A Roadmap for U.S. Mobilization*, now underway for publication later in 2003. Its economic attractiveness is likely to be clear just from private internal cost, without counting the many large externalities of oil dependence.

Myth #20. The Bush Administration's hydrogen program is just a smokescreen to stall adoption of the hybrid-electric and other efficient car designs available now, and wraps fossil and nuclear energy in a green disguise.

Most environmentalists — perhaps resentful that President Bush has stolen some of their thunder — think FreedomCAR and the Hydrogen Fuel Initiative are a stall, not a leapfrog, and consider the President's hydrogen announcement mere greenwash for stealthy, rhetorically attractive, but generally anti-environmental substantive policies. (Conversely, *The Wall Street Journal*'s editorial board — apparently as unwilling to credit any idea environmentalists agree with as environmentalists are to credit any idea the President agrees with — attacks the President's "reasons for funding hydrogen cars [as] neither smart nor honest."[2]) The White House's opposition to significant near-term gains in car efficiency unfortunately foments the doubtless unworthy suspicion that hydrogen is being wielded as a political weapon of mass distraction. That lingering odor would best be dispelled by developing and deploying hydrogen to displace most or all petroleum motor fuel in the long run while *also* saving a lot of oil in the short run by aggressively encouraging hybrid-electric powertrains and other straightforward, available technological improvements that cost less than today's gasoline. Policy and credibility would also be improved by adding hydrogen dollars to the energy R&D budget rather than appearing to take them out of efficiency and renewables accounts.

Both the long-term hydrogen goals and the short-term car-efficiency goals are worthy, in sequence and in coordination; they also support each other, so there's no reason not to do both. Let the short-term measures support the long- term ones (*e.g.*, by making cars more efficient and electric traction cheaper), and let them both compete fairly. If we don't, the losers will be Detroit (as foreign competitors take more market share), the Earth, American customers and taxpayers, and their economy, public health, and global security. But if we do, then hydrogen advocates' utopian visions of a cleaner, safer, and more prosperous world may be right on the money.

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Flugzeuge mit Wasserstoffantrieb," Airbus Deutschland GmbH, Hamburg, 6 Dec. 2001, www.haw-hamburg.de/pers/Scholz/dglr/hh/text_2001_12_06_Cryoplane.pdf.

[36] W. Zittel, "Hydrogen in the Energy Sector," Ludwig-Bölkow-Systemtechnik GmbH, 1996, www.hydrogen.org/Knowledge/w-I-energiew-eng.html.

[37] A.D. Robinson, "Hydrogen Hype," *Access to Energy* **30**(9):1 (April 2003).

[38] A. Bain & W.D. Van Vorst, "The *Hindenburg* tragedy revisited: the fatal flaw found," *Intl. J. Hydr. En.* **24**:399–403 (1999); A. Bain & U. Schmidchen, "Afterglow of a Myth: Why and how the 'Hindenburg' burnt," www.dwv-info.de/pm/hindbg/hbe.htm.

[39] See ref. 53.

[40] M.R. Swain, "Fuel Leak Simulation," www.eren.doe.gov.

[41] C.E. Thomas, personal communication, 4 June 2003.

[42] M.A. Weiss *et al.*,

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nologies and cost challenges for automotive and stationary applications," in W. Vielstich *et al.*, eds., *Handbook of Fuel Cells—Fundamentals, Technology and Applications*, Wiley (Chichester), 2003 (data from late 2001).

[71] Thomas (ref. 53 at p. 26) notes that gas-reformer/PEM-fuel-cell systems will be significantly more fuel-efficient than microturbines, but only slightly more fuel-efficient than engine-generators. Their advantage over the latter will come rather from lower noise, emissions, and maintenance.

[72] The normally assumed need for ~\$30–100/kW fuel cells to compete with internal-combustion engines can be relaxed by about threefold — probably more from a whole-platform perspective — through better platform physics, as described in Myth #7 and its sidebar.

[73] H. Tsuchiya & O. Kobayashi ("Fuel Cell Cost Study by Learning Curve," EMF/HASA International Energy workshop, Stanford University, 18–20 June 2002) predict a somewhat smaller range of 14–26% per doubling.

[74] T.E. Lipman & D. Sperling, "Forecasting the Costs of Automotive PEM Fuel Cell Systems Using Bounded Manufacturing Progress Functions," Intl. Workshop on Experience Curves for Policy Making: The Case of Energy Technologies, Stuttgart, 10–11 May 1999, International Energy Agency (Paris).

[75] See www.hydrogen.org/h2cars/overview/main00.html

1998, and reproduced in the ORNL/LBNL App. E-3 to ref. 129, shows an average of $0.0296/kWh (mixed current $), about one-third higher than EIA's edited data for the same years, but let's conservatively assume EIA's edited lower figures for 1996–2000. It's typically much cheaper to deliver electricity through the existing grid (assuming it has spare capacity) than to deliver centrally produced hydrogen in a new distribution system, so let's assume that method. RMI's *Small Is Profitable* (www.smallisprofitable.org) shows at pp. 217–218 that in 2000 $, the embedded

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[117] More precisely, the President’s FY2004 budget cuts efficiency and renewables accounts by $86 million and proposes $39 million for hydrogen, the majority of it from nonrenewable sources.

[118] A.B. Lovins, “FreedomCAR, Hypercar®, and Hydrogen,” invited lead testimony to Energy Subcommittee, U.S.House of Representatives Science Committee, 26 June 2002, www.rmi.org/sitepages/pid175.php.

[119] R. Wurster & W. Zittel, *Hydrogen Energy*, LBST, Ottobrunn, Germany, 1994, www.hydrogen.org/Knowledge/main.html; see also ref. 31.

[120] See ref. 31.

[121] See ref. 113.

[122] Actually the 2004 budget appears to have slightly more R&D dollars for nuclear and fossil fuels than for renewables as hydrogen sources, but perhaps there’s more than one way to keep score or he’s assuming, in line with Administration policy, that nuclear power is “sustainable.”

[123] D. Garman, *op. cit. supra* (ref. 51).

[124] A compressed-hydrogen fuel-cell car using steam-reformed natural gas releases only about half as much CO_2 per mile as a normal gasoline car — or as a liquid-hydrogen fuel-cell car using electricity from 60%-efficient gas-fired combined-cycle power stations. However, a compressed-hydrogen fuel-cell car using electrolysis powered by the average U.S. power station (51% of 2001 U.S. electricity was coal-fired) releases nearly four times as much CO_2 per mile as a typical gasoline car. See ref. 53.

[125] S. Pacala & R. Socolow, “Carbon Mitigation Initative: Second Year Annual Report,” January 2003, www.princeton.edu/~cmi/summary/Second annual report.pdf, p. 4.

[126] President’s Committee of Advisors on Science and Technology, *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century*, 1997, p. 6-35, www.ostp.gov/Energy/index.html.

[127] See note 43. The equivalent efficiency at HHV gas input (conventional for purchase contracts and prices) is 80%.

[128] The Oak Ridge National Laboratory *Transportation Energy Data Book*, 22nd edn., at p. 2-6 (ref. 103), states that U.S. domestic light vehicles in 2000 consumed 15.705 quadrillion BTU of gasoline and diesel fuel (HHV). Quintupled efficiency would reduce this to 3.14 QBTU (HHV). At the HHV reformer efficiency of 80%, this requires gas input of 3.83 QBTU (neglecting reformer electric input and net retail compression energy) — 20.2% of 2000 U.S. production of dry natural gas, or 16.3% of 2000 U.S. consumption of natural gas. This is consistent with Shell’s scenario (ref. 97) in which a one-fourth-fuel-cell OEbhf4 780.06 cm BT 41 0 0 -41 286 1165 Tm /F1.0 1 Tf(S. Pacala1le.)044a:rchase c

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in a personal communication on 1 May 2003, where he concludes that based on those data, “a [natural-gas] leakage rate of 1% is reasonable. The highest rate could be 1.5%. The rate would definitely not go to the 5–10% range.”

[143] Zittel & Altmann, *op. cit. supra*, ref. 136.

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