Twenty Hydrogen Myths

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Abstract

Recent public interest in hydrogen has elicited a great deal of conflicting, confusing, and often ill-informed commentary. This peer-reviewed white paper offers both lay and technical readers, particularly in the United States, a documented primer on basic hydrogen facts, weighs competing 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

Rocky Mountain Institute is an independent, entrepreneurial, nonprofit applied research center founded in 1982. Its ~50 staff foster the efficient and restorative use of resources to make the world secure, just, prosperous, and life-sustaining. The majority of its ~$7-million annual revenue is earned by consultancy, chiefly for the private sector; the rest comes from foundation grants and private gifts. Much of the context of its work is summarized in *Natural Capitalism* (www.natcap.org). Donations are welcome and tax-deductible (#74-2244146). RMI is at 1739 Snowmass Creek Road, Snowmass, CO 81654, phone + 1 970 927-3851, fax -4178.

Table of Contents

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20 June 2003

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 because like oil and gas, but unlike electricity, it can be stored in large amounts (albeit often at higher storage cost than hydrocarbons), and can be made from almost any energy source and used to provide almost any energy service. Like electricity, hydrogen is an extremely high-quality form of energy, and can be so readily converted to electricity and back that fuel-cell pioneer Geoffrey Ballard suggests they be thought of together as a fungible commodity he calls "Hydricity™."

- The reason hydrogen isn't an energy *source* is that it's almost never found by itself, the way oil and gas are. Instead, it must first be freed from chemical compounds in which it's bound up. There are broadly three ways to liberate hydrogen: using heat and catalysts to "reform" hydrocarbons or carbohydrates, or electricity to split ("electrolyze") water, or experimental processes, based typically on sunlight, plasma discharge, or microorganisms.[14] All devices that produce hydrogen on a small scale, at or near the customer, are collectively called "hydrogen appliances" to distinguish them from traditional large-scale industrial production.
- Fossil-fuel molecules are combinations of carbon, hydrogen, and various other atoms. Roughly two-thirds of the fossil-fuel atoms burned in the world today are hydrogen. (However, hydrogen yields a smaller share of fossil-fuel energy, because its chemical bonds are weaker than carbon's.) The debate is about whether combusting the last third of the fossil fuel — the carbon — is necessary; whether it might be cheaper and more attractive not to burn that carbon, but only to use the hydrogen; and to what degree that hydrogen should be replaced by hydrogen made with renewable energy sources.
- Using hydrogen as a fuel, rather than burning fossil fuels directly, yields only water[15] (and perhaps traces of nitrogen oxides if used in a high-temperature process). This can reduce pollution and climate change, depending on the source of the hydrogen. But when journalists write that hydrogen can "clean the air,"[16] that's shorthand for keeping pollutants out of the air, not removing those already there.
- Hydrogen is the lightest element and molecule. Molecular hydrogen (two hydrogen atoms, H_2) is eight times lighter than natural gas. Per unit of energy contained, it weighs 64% less than gasoline or 61% less than natural gas: 1 kilogram (2.2 lb) of hydrogen has about the same energy as 1 U.S. gallon of gasoline, which weighs not 2.2 but 6.2 pounds.[17] But the flip side of lightness is bulk. Per unit of *volume*, hydrogen gas contains only 30% as much energy as natural gas, both at atmospheric pressure. Even when hydrogen is compressed to 170 times atmospheric pressure (170 bar), it contains only 6% as much energy as the same volume of gasoline. Hydrogen is thus most advantageous where lightness is worth more than compactness, as is often true for mobility fuels.
- One of the biggest challenges of judging hydrogen's potential is how to compare it fairly and consistently with other energy carriers. Fossil fuels are traditionally measured in cost, volume, or mass per unit of *energy content*.[18] That's valid only if the fuels being compared are all used in similar devices and at similar efficiencies, so all yield about the same amount of energy service. But that's not valid for hydrogen. Fuel cells (explained further in Myth #6) are not subject to the same thermodynamic limits as fuel-driven engines, because they're electrochemical devices, not heat engines. A hydrogen fuel-cell car can therefore convert hydrogen energy into motion about 2–3 times as efficiently as a normal car converts gasoline energy into motion: depending on how it's designed and run, a good fuel-cell system is about 50–70% efficient, hydrogen-to-electricity,[19] while a typical car engine's efficiency from gasoline to output shaft averages only about 15–17%

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 made and consumed onsite costs about $0.71/kg. [23] That's equivalent in *energy* content to $0.72 per gallon of gasoline.[24] But *per mile driven* — which is the objective — it's equivalent to about one-third to one-half that price, *i.e.*, to about $0.24–0.36/gallon-equivalent, because of the 2–3-fold greater efficiency of a hydrogen fuel cell than a gasoline engine in running a car. Of course, the *price* of hydrogen *delivered* into the car's fuel tank will be much higher. For example, DOE says the delivered price of industrial liquid hydrogen is about $2.2–3.1/kg. If it could be delivered into the tank of a car for the same price, it would be roughly equivalent *per mile* to $1-a-gallon gasoline. Thus it can cost several times as much to deliver liquid hydrogen as to produce it. (Fortunately, as we'll see, gaseous hydrogen can be produced at a filling station and put into the car for well under $2/kg.) Price also depends on hydrogen purity. So to assess hydrogen's price or cost or value or benefit meaningfully, we need to know how it'll be used, whether it's pure enough for the task, whether it's delivered to the task, and how much of the desired work it actually does.

Different questions yield different answers

So much for the basics. What's different about Rocky Mountain Institute's perspective that underlies this paper?

- RMI believes that radical but practical and advantageous efficiency improvements at three levels — vehicles, energy distribution, and overall energy infrastructure — can make the hydrogen transition rapid and profitable.
- At least for the next decade or two, RMI envisions a distributed model for hydrogen production and delivery that integrates the gas, electricity, building, and mobility infrastructures. Instead of building a costly new distribution infrastructure for hydrogen, we'd use excess capacity inherent in the existing gas and electricity distribution infrastructures, then make the hydrogen locally so it requires little or no further distribution. Only after this decentralized approach had built up a large hydrogen market in buildings and vehicles could centralized hydrogen production merit much investment, except in special circumstances.

- 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 *less* 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 *less* natural gas than business-as-usual.**
- **A rapid hydrogen transition will probably be *more* 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.**

Now for the currently prevalent hydrogen myths, and what their correction implies about desirable courses of action. Writing for a mainly U.S. audience, we'll use a mixture of U.S. and international units of measurement.

Twenty myths

Myth #1. A whole hydrogen industry would need to be developed from scratch.

Producing hydrogen is already a large and mature global industry, using at least 5% of U.S. natural gas output. Globally, about 50 million metric tons of hydrogen is made for industrial use each year. That's over half a trillion cubic meters measured at atmospheric pressure.[25] The U.S. Department of Energy (DOE) reports[26] that about 48% of global hydrogen production is reformed from natural gas, 30% from oil, and 18% from coal (chiefly in China and South Africa for producing nitrogen fertilizer; half the world's hydrogen goes into ammonia-based fertilizer). Only 4% of the world's hydrogen comes from electrolysis, because that process can compete with reforming fossil fuels only under three main conditions: with very cheap electricity, generally well under 2¢/kWh (see Myth #9 below); if the hydrogen is a byproduct (about 2%, for example, is unintentionally made during "chloralkali" electrolytic chlorine production); or perhaps if the producer is charged for carbon emissions and has a carbon-free source of electricity but no way to sequester (keep out of the atmosphere) carbon released from reforming fossil fuels.

U.S. hydrogen production is at least one-fifth and probably nearer one-third of the world total,[27] is equivalent to ~1.8% of total U.S. energy consumption, and comes ~95% from natural gas at ~99% purity from steam reforming and associated cleanup processing.[28] Roughly 47% of U.S. or 37–45% of world hydrogen production is reportedly used in refineries;[29] it is made onsite, mostly by steam reforming of gas or oil, and is used mainly to make gasoline and diesel fuel. Most hydrogen production by refineries is deliberate, used to make hydrogen-rich refined products or to remove sulfur from them; some is a byproduct of making aromatic compounds. The rest of the world's hydrogen output goes to ammonia fertilizer, methanol, petrochemicals, edible fats and oils, metal production, microchips, and other products, and a little to special industrial furnaces. World hydrogen production is reportedly doubling about every decade, driven by refineries' need to make lower-sulfur fuels and by other growth industries. Usage for fertilizer has been relatively flat for the past decade, and usage for methanol is growing more slowly (roughly with GDP) as prospects fade for wide use of methanol-derived MTBE gasoline additive, so the biggest growth market for industrial hydrogen appears to be refineries.

The industrial infrastructure for centralized hydrogen production already exists. Throughout industry, most hydrogen is currently made at large plants and is used at the industrial site or nearby. There are ~1,500 km (~930 miles) of special hydrogen pipelines (720 km or 446 miles in North America) operating at up to 100 bar.[30] Moving hydrogen gas through pipelines takes about half as much of its energy as is currently lost when transporting electricity, and the pipeline is far smaller — a 1.7-meter-diameter hydrogen pipeline at 70 bar delivers 16 GW, whereas a 60-meter-tall pylon with three pairs of ±500-kVDC power lines delivers only 9 GW.[31] Hydrogen is less dense and takes more compressor energy than natural gas, but also flows better, so transporting hydrogen through existing natural-gas pipelines would deliver only ~20–25% less energy, net of compressor consumption[32] — thus enabling hydrogen's more efficient end-use to deliver more service than from the original natural gas flow. Pipelines may also be cheaper, easier to site, and more secure than aboveground high-voltage electric transmission lines.

Hydrogen pipelines normally carry compressed hydrogen gas, not super-cold liquid hydrogen. Only about 1–3 thousandths of all hydrogen produced is liquefied and cryogenically piped, mainly to NASA launch pads for rocket fuel — an ideal use for a fuel whose density is about as low as the denser grades of Styrofoam.[33]

Centralized hydrogen production has coevolved with centralized consumption by major industrial plants. Yet most future uses of hydrogen are not centralized; they'll serve millions of dispersed customers. This dispersed pattern of usage calls for a different pattern of production, not so much in centralized plants as in small ones near the customers. This can often deliver cheaper hydrogen, because reformers and electrolyzers, which both work well at a small scale, can make hydrogen delivery simpler or unnecessary: instead, they'll leverage the existing gas and electricity distribution grids, especially during off-peak periods when (by definition) they have excess capacity. Driven by the economics of supply and demand, the hydrogen industry will evolve organically at many scales and for many uses — if it's not unduly retarded by myths.

Myth #2. Hydrogen is too dangerous, explosive, or "volatile" for common use as a fuel.

The hydrogen industry has an enviable safety record spanning more than a half-century. Any fuel is hazardous and needs due care, but hydrogen's hazards are different and generally more tractable than those of hydrocarbon fuels.[34] It's extremely buoyant — 14.4 times lighter than air (natural gas is only 1.7 times lighter than air). Hydrogen is four times more diffusive than natural gas or 12 times more than gasoline fumes, so leaking hydrogen rapidly disperses up and away from its source.[35] If ignited, hydrogen burns rapidly with a nonluminous flame that can't readily scorch you at a distance, emitting only one-tenth the radiant heat of a hydrocarbon fire and burning 7% cooler than gasoline. Although firefighters dislike hydrogen's clear flame because they need a viewing device to see it in daylight, victims generally aren't burned unless they're actually in the flame, nor are they choked by smoke.

Hydrogen mixtures in air are hard to explode, requiring a constrained volume of elongated shape. In high-school chemistry experiments, hydrogen detonates with a "pop" when lit in a test tube, but if it were in free air rather than a long cylindrical enclosure, it wouldn't detonate at all. Explosion requires at least twice as rich a mixture of hydrogen as of natural gas, though hydrogen's explosive potential continues to a fourfold higher upper limit. Hydrogen does ignite easily, needing 14 times less energy than natural gas, but that's of dubious relevance because even natural gas can be ignited by a static-electricity spark.[36] Unlike natural gas, however, leaking hydrogen encountering an ignition source is far likelier to burn than to explode, even inside a building, because it burns at concentrations far below its lower explosive limit. Ignition also requires a fourfold higher minimum concentration of hydrogen than of gasoline vapor. In short, in the vast majority of cases, leaking hydrogen, if lit, will burn but not explode. And in the rare cases where it might explode, its theoretical explosive power per unit volume of gas is 22 times weaker than that of gasoline vapor. It is not, as has been claimed, "essentially a liquid or gaseous form of dynamite."[37]

Contrary to a popular misunderstanding, these safety attributes actually helped save 62 lives in the 1937 *Hindenburg* disaster. An investigation by NASA scientist Dr. Addison Bain found[38] that the disaster would have been essentially unchanged even if the dirigible were lifted not by hydrogen but by nonflammable helium, and that probably nobody aboard was killed by a hydrogen fire. (There was no explosion.) The 35% who died were killed by jumping out, or by the burning diesel oil, canopy, and debris (the cloth canopy was coated with what nowadays would be called rocket fuel). The other 65% survived, riding the flaming dirigible to earth as the clear hydrogen flames swirled harmlessly above them. This would hardly be the case if an aircraft with only liquid hydrocarbons caught fire while aloft. It emphasizes that hydrogen is generally at least as safe as natural gas or LPG, and is arguably inherently safer than gasoline,[39] although the character of their risks is not identical. For example, leaking hydrogen gas will accumulate near the ceiling of an airtight garage, while gasoline fumes or propane will accumulate near the floor — a greater risk to people because they're typically near the floor, not the roof. Standing in a carpet of fire is far more dangerous than standing below a nearly non-luminous clear flame that goes upwards.

Lingering perceptions that hydrogen is unusually dangerous are likely to be dispelled by the kinds of compelling videotaped demonstrations now becoming available, such as a comparison of a hydrogen fire with a gasoline fire. First, a hydrogen leak was created, assuming a very unlikely triple failure of redundant protective devices (industry norms for hydrogen leak detection and safety interlocks are convincingly effective). The tested leak, deliberately caused at the highest-pressure location, discharged the entire 1.54-kg hydrogen inventory of the fuel-cell car in ~100 s, but the resulting vertical flame plume raised the car's interior temperature by at most 1–2 F° (0.6–1.1 C°), and its outside temperature nearest the flame by no more than a car experiences sitting in the sun. The passenger compartment was unharmed. But then in the second test, a 2.5-fold-lower-energy leak from a 1.6-mm (1/16") hole in a gasoline fuel line gutted the car's interior and would have killed anyone trapped inside.[40] Because the hydrogen-leak test didn't damage the car, both tests were conducted successively *using the same car*.[41]

Finally, of course, there is no connection whatever between ordinary hydrogen gas, whose chemical reactions make it useful as a fuel, and the special isotopes whose thermonuclear reactions power hydrogen bombs. A hydrogen bomb can't be made with ordinary hydrogen, nor can the conditions that trigger nuclear fusion in a hydrogen bomb occur in a hydrogen accident; they're achieved, with difficulty, only by using an atomic bomb.

Myth #3. Making hydrogen uses more energy than it yields, so it's prohibitively inefficient.

Any conversion from one form of energy to another consumes more useful energy than it yields. If it could do the opposite, creating energy out of nothing, you could create a perpetual-motion machine violating the laws of physics. Conversion losses are unavoidable; the issue is whether they're worth incurring. If they were intolerable as a matter of principle, as Myth #3 implies, then we'd have to stop making gasoline from crude oil (~73–91% efficient from wellhead to retail pump[42]) and electricity from fossil fuel (~29–35% efficient from coal at the power plant to retail meter). Such conversion losses are thus not specific to producing hydrogen. Hydrogen production is typically about 72[43] to 85[44] percent efficient in natural-gas reformers or ~70–75% efficient in electrolyzers;[45] the rest is heat that may also be reusable. (These efficiency figures are all 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 byproduct 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 utilization of intermittent sources like wind. Once all the distributed benefits are accounted for, using hydrogen for peak storage may be worthwhile, particularly in cities with transmission constraints (such as Los Angeles, San Francisco, Chicago, New York City, and Long Island). Such applications may be able to justify capital costs upwards of \$4,000/kW. Another attractive use of large-scale hydrogen storage would be in places like New Zealand or Brazil, whose hydroelectric systems have too little storage (12 weeks in NZ) to provide resilience against drought — but whose snowmelt or rainy seasons provide cheap surplus hydropower that could be stored as hydrogen, even in old gas-fields.

Many people assume that fuel makes more electricity if burned in an efficient power plant than if converted into hydrogen and then used in a fuel cell. This is not necessarily true. For example, using gasified biomass in a high-temperature molten-carbonate fuel cell, which needs no reformer, looks economically promising, even though reforming the biomass into hydrogen would be only about 60–65% efficient — worse than for reforming natural gas.[48]

Myth #4. Delivering hydrogen to users would consume most of the energy it contains.

Two Swiss scientists recently analyzed the energy needed to compress or liquefy, store, pipeline, and truck hydrogen.[5] Although one can quibble with details, their net-energy figures are basically correct — but not their widely quoted conclusion that because hydrogen is so light, "its physical properties are incompatible with the requirements of the energy market. Production, packaging, storage, transfer and delivery of the gas…are so energy consuming that alternatives should be considered." In fact, their paper simply catalogues certain hydrogen processes that most in the industry have *already* rejected, except in special niche markets, because they're too costly, including: pipelines many thousands of kilometers long, liquid-hydrogen systems[49] (except for rockets and aircraft[50]), and delivery in steel trucks weighing more than 100 times as much as the hydrogen carried. This argument serves the business interests of its publisher, the Methanol Institute, which promotes methanol over hydrogen, but it does not present a balanced view of how the hydrogen industry is actually evolving.

The Swiss authors focus almost exclusively on the costliest production method — electrolysis. They admit that reforming fossil fuel is much cheaper, but they reject it because, they claim, it releases more CO_2 than simply burning the original hydrocarbon. This claim reflects the common error of overlooking the high efficiency of the last link in the chain — the fuel cell. For example, even under conservative assumptions about car design, a good reformer making hydrogen for a fuel-cell car releases about 40%[12] to 67^+% less CO_2 per mile than burning hydrocarbon fuel in an otherwise identical gasoline-engine car. That's because the fuel cell is 2–3 times more efficient than the internal-combustion engine, and methane has twice the hydrogen/carbon ratio of gasoline.[51] (It's possible, with some difficulty, to reach contrary conclusions by making sufficiently peculiar design assumptions, and some U.S. studies have done so, but we should be comparing good designs, not bad ones.) Or consider fuel cells in buildings: a fuel cell fueled by a miniature natural-gas reformer will convert gas to delivered electricity more efficiently than a microturbine or a classical gas-fired power plant, and comparably to an engine generator or a combined-cycle power plant. It also offers highly efficient and convenient cogeneration opportunities (*i.e.*, reusing otherwise wasted heat) that the offsite power plants do not.

The Swiss authors' third distortion is to analyze only centralized ways to make hydrogen, requiring costly and energy-intensive delivery to customers — the source of most of their criticisms. Partly for that very reason, industry strategists, and the profitable hydrogen transition strategy published by RMI[52] (see sidebar), instead suggest — at least for the next couple of decades — *de*centralized production at or near the customer, using natural gas and electricity that, unlike hydrogen, are *already* being distributed to most customers. Decentralized natural-gas reformers would normally pay a higher price for natural than the big industrial reformers that now produce almost all industrial hydrogen[53], yet the small reformers can usually *deliver* hydrogen more cheaply — because they avoid all of the costly hydrogen-delivery problems that the Swiss authors criticize. Moreover, contrary to a common notion, greater compactness and thermal integration can make miniature reformers as efficient as big ones, or even slightly more efficient.[54]

Box 1: RMI's suggested hydrogen transition strategy[55]…

- starts with decentralized natural-gas reformers (or occasionally electrolyzers, chiefly at very small scale or where cheap power is available) in buildings (which use two-thirds of all electricity), where their ability to deliver premium power quality and reliability and to use byproduct heat for space-conditioning makes them cost-effective even at initially high fuel-cell costs — especially in areas with congested distribution grids;
- begins the deployment of hydrogen-fuel-cell cars with fleets that return to the depot for nightly refueling;
- then leases general-market hydrogen-fuel-cell cars to people who work in or near the buildings where fuel cells have by then been installed;
- uses the spare capacity of those buildings' hydrogen appliances (since they're sized for peak building loads that seldom occur) to make and store extra hydrogen, then sell it to fuel cars parked nearby, improving the economics of the fuel-cell system while also repaying most or all of the cars' cost of ownership by selling electricity and other services back to the electric grid when and where that's most valuable;
- as the hydrogen appliances made for buildings become cheaper, deploys them also outside buildings, *e.g.*, in filling stations — using natural gas or electricity (whichever is cheaper), fueled by distribution capacity that's already built and paid for, to make hydrogen onsite with ~50–82% lower carbon emissions per mile[56] than today's gasoline cars; and
- ultimately expands hydrogen competition by adding hydrogen production from other renewable sources, as well as from cost-effective climate-safe gas, oil, or coal conversion in more centralized plants that can separate and safely store ("sequester") the carbon. This greater supply diversity, where justified, completes the gradual, largely self-financing transition from a high-carbon to a low-carbon ("low-carbs") to a no-carbon ("no-carbs") energy system — perhaps the ultimate Atkins diet for the planet.

In the long run, if central hydrogen production does make sense, mainly to simplify carbon sequestration and thus protect the climate,[57] this would generally be done not thousands of kilometers away,[58] but near cities — for example, at existing oil refineries, which could turn into merchant hydrogen plants.[59] If it proved necessary to pipe the separated CO_2 to a remote site for disposal, that's OK: even over very long distances, it's much cheaper to pipe the CO_2 than the hydrogen. Moreover, where the output of a central-electric generator can produce competitive hydrogen, it'll typically cost far less to ship the electricity through existing offpeak transmission capacity than to make the hydrogen at the big power plant and then pipeline it to customers.

Myth #5. Hydrogen can't be distributed in existing pipelines, requiring costly new ones.

If remote, centralized production of hydrogen eventually *did* prove competitive or necessary, as this myth assumes, then existing gas transmission pipelines could generally be converted to hydrogen service, *e.g.* by adding polymer-composite liners, similar to those now used to renovate old water and sewer pipes, plus a hydrogen-blocking metallized coating or liner (analogous to those used in composite hydrogen tanks), and by converting the compressors. Exterior composite wraps are also available if the pipelines need strengthening. Even earlier, existing and unmodified pipelines could safely carry a mixture of hydrogen and methane ("Hythane®"), up to a certain hydrogen fraction, to "stretch" their natural gas; users of fuel cells could perhaps then separate the two gases with special membranes. (The Dutch gas giant Gasunie is studying these options with a 62-member European consortium.) Some newer pipelines may already have hydrogen-ready alloys, valves, and seals. Others can be used to make all future pipelines hydrogen-compatible, as Japan intends for its major Siberia-China-Japan gas pipeline;[60] this shouldn't cost extra.[61] Metallurgical issues with hydrogen can generally be avoided by using lower-carbon alloys, moderate and fairly steady pressures, and exterior composite wraps if needed for strength.[62] No special safety issues are expected in converting gas pipelines to hydrogen service; indeed, a 200-mile crude-oil pipeline has already been converted to hydrogen service.[63] New methods of making hydrogen pipelines, such as field pultrusion of composites, may prove attractive.

As for natural-gas distribution pipes, many older systems are already largely or wholly hydrogen-compatible because they were originally built for the "town gas" (synthetic coal-gas that's ~50–60% hydrogen by volume) that used to be piped into homes in many of the world's major cities, and still is in parts of China and South Africa. However, the burner-tips, meters, and other minor components could require retrofit.[64] Combustion appliances, unlike fuel cells, may not run much more efficiently with hydrogen than with natural gas, so they may deliver less service per unit of flow; this emphasizes the importance of using hydrogen where it offers a comparative advantage — as economics would also dictate.

Myth #6. We don't have practical ways to run cars on gaseous hydrogen, so cars must continue to use liquid fuels.

Turning wheels with electric motors has well-known advantages of torque, ruggedness, reliability, simplicity, controllability, quietness, and low cost. Heavy and costly batteries have limited battery-powered electric cars to small niche markets, although the miniature lithium batteries now used in cellphones are severalfold better than the batteries used in electric cars. But California regulators' initial focus on battery cars had a huge societal value because it greatly advanced electric drivesystems. The only question is where to get the electricity. Hybrid-electric cars now on the market from Honda and Toyota, and soon from virtually all automakers, make the electricity with onboard engine-generators, or recover it from braking. These "hybrid-electric" designs provide all the advantages of electric propulsion without the disadvantages of batteries. Still better will be fuel cells — the most efficient (~50–70% from hydrogen to direct-current electricity), clean, and reliable known way to make electricity from fuel. Nearly all significant automakers now have major fuel-cell car development programs.

Remember the high-school chemistry experiment of electrolysis — splitting water with an electric current and making hydrogen and oxygen bubble out of the test-tube? Fuel cells reverse this process by chemically recombining hydrogen and oxygen on a special membrane, at temperatures as low as 160–190˚F (much higher in some types). This electrochemical reaction, with no combustion, produces electricity, pure hot water suitable for a coffee machine in the dashboard, byproduct heat suitable for heating or cooling the vehicle, and nothing else. Invented in 1839, used in space shuttles since 1965, and demonstrated in a passenger vehicle (GM's *Electrovan*) in 1966, fuel cells have been widely used for decades in aerospace and military applications, where they're prized for their ruggedness, simplicity, and reliability. Now they're rapidly emerging as power sources for portable electronics and home appliances (such as hand tools and vacuum cleaners), due to market by 2004–05.[65] Fuel cells are already competitive for buildings when installed in the right place and used in the right way.[66] So are certain industrial niche markets.[67]

In the past decade, breakthroughs in materials and manufacturing engineering have reduced the need for precious-metal catalysts (especially when using pure hydrogen) by more than 20-fold, [68]and have raised the power density and cut the cost of the most common type of fuel cell[69] by 10-fold. [70] Continuing advances in both the fuel-cell "stack" and the other components in the fuel-cell system now make it realistic to expect fuel cells to start competing with grid electricity in general use (*i.e.*, at about $500–800/kW if no distributed benefits are counted[71]) within this decade, and even with internal-combustion engines by around 2010 in carefully integrated vehicle designs needing ~$100–300/kW.[72]

In the next few years, more durable membranes and manufacturable designs are widely expected to permit rapidly expanding mass production of fuel cells for both vehicles and buildings. Once those innovation triggers have occurred, then as for most other manufactured goods, real cost should fall by ~20–30%[73] for each doubling of cumulative production until limited by the cost of the basic materials. In very high volumes, the projected production cost of a low-temperature fuel-cell stack can ultimately reach on the order of $30–60/kW, not far from the ~$20/kW cost of generator-equipped internal-combustion engines, which have been refined for more than a century and are produced in enormous volumes.[74] RMI's integrated transition strategy (sidebar, Myth #4) is indifferent to whether fuel cells first become durable, as buildings need, or cheap, as vehicles need: if they become durable first, enough can be made for buildings — which use two-thirds of U.S. electricity — to make them cheap enough for vehicles, while if they first become cheap enough for vehicles, they can also be used in buildings and renovated or replaced as needed. Either way, each market accelerates the other by building production volume, cutting cost, and creating profitable linkages.

Fuel-cell testing for vehicles is well advanced. As of mid-2003, manufacturers have tens of fuel-cell buses and upwards of 100 fuel-cell cars on the road: an authoritative German compilation[75] lists 156 kinds of fuel-cell concept cars and 68 demonstration hydrogen filling stations. Honda and Toyota are leasing small numbers of fuel-cell cars in California; six other automakers plan to follow suit during 2003–05 and at least ten more by 2010. Many kinds of military vehicles for land and sea are testing fuel cells, long used in submarines. So are some heavy trucks, which spend up to half their engine runtime idling because they have no auxiliary power unit (the corresponding figure for Abrams tanks exceeds 60–80%). Fedex and UPS reportedly plan to introduce fuel-cell trucks by 2008. Many applications are being pursued for scooters, recreational vehicles, boats, and even large ships. All these developments will learn from each other. Collectively they will increase fuel-cell production volume and hence reduce cost. A Deutsche Shell director predicted in 2000 that half of all new cars and a fifth of the car fleet will run on hydrogen by 2010, while the German Transport Minister forecast 10% of new German cars.

Some automakers formerly assumed that they must extract hydrogen from gasoline (or methanol) aboard cars, using portable reformers, for either or both of two reasons:

- Tanks of compressed hydrogen would be too bulky, because the hydrogen has ~10 times less energy per unit volume than liquid fuels.
- It would be too hard, slow, or costly to replace today's gasoline fueling infrastructure with a new hydrogen fueling infrastructure. Moreover, there's an obvious chicken-and-egg problem: you wouldn't want to build a filling station with no cars to buy its hydrogen, nor buy a hydrogen car with nowhere to refuel it.

As noted in Myths #5, 9, and 10, both of these problems have now been solved, so few automakers still favor onboard gasoline reformers. That's good, because those reformers are very difficult and problematic (*e.g.*, in their startup times), and would cut gasoline-tank-to-wheels efficiency to or below that of a good gasoline-engine car. Since almost all automakers now agree that reformers should be at or near the filling station, not aboard the car, there's no longer any reason to reform gasoline: natural gas is much cheaper, and is easier to reform. Hydrogen will thus displace gasoline altogether, saving the energy, money, and hydrogen now used to make it (Myth #11).

Similar arguments apply to methanol. This hydrogen-rich liquid, typically made from natural gas, is easier to distribute, restore, and reform than gasoline, and can be used directly in some kinds of fuel cells that could be attractive for household appliances and tools, or for such portable electronics as computers, cellphones, hearing aids, or individual military equipment. However, methanol is less attractive than direct hydrogen as a vehicular fuel, because it has a higher lifecycle cost,[76] higher carbon releases, and considerable toxicity (2–7% methanol in a liter of water, with which it mixes readily, is too little to taste, but could be lethal if swallowed). The transportation industry already faces heavy costs from having invested to switch to the methanol-derived but far less toxic gasoline oxygenate additive MTBE (methyl *tert*-butyl ether), only to find it banned after it leaked from underground storage tanks into groundwater.[77] This unhappy experience makes the industry understandably wary of methanol, and several major oil companies have made clear that they reject methanol deployment. Except for the kinds of special uses mentioned above, or countries with poor or very costly natural-gas distribution, it's also unclear why one would wish to turn natural gas into methanol, move it to another site, and there reform it into hydrogen, rather than just transporting the natural gas in the existing gas grid to the point of hydrogen use and reforming it there. In gas-short countries, many other liquid feedstocks, such as medium and heavy oils, dimethyl ether, LPG, and vegetable oils will also compete with methanol as distributed reformer feedstocks.

Myth #7. We lack a safe and affordable way to store hydrogen in cars.

This problem was solved several years ago. Such firms as Quantum (partly owned by GM) and Dynetek now sell filament-wound carbon-fiber tanks lined with an aluminized polyester bladder instead of the traditional solid metal liner (cutting weight by half and materials cost by a third). Such carbon tanks have ~9–13 times the performance of an aluminum or steel tank, but can't corrode and are extremely rugged and safe, unscathed by crashes that flatten steel cars and shred gasoline tanks. The car isn't driving around with highly pressurized hydrogen pipes, either, because the hydrogen is throttled to the fuel cell's low pressure before it leaves the tank. Such aerospace-style tanks holding up to 700 bar (~10,000 psi) and proven over 1,655 bar (~24,000 psi) have been tested by GM and others in fuel-cell cars and are legally approved in Germany; U.S.

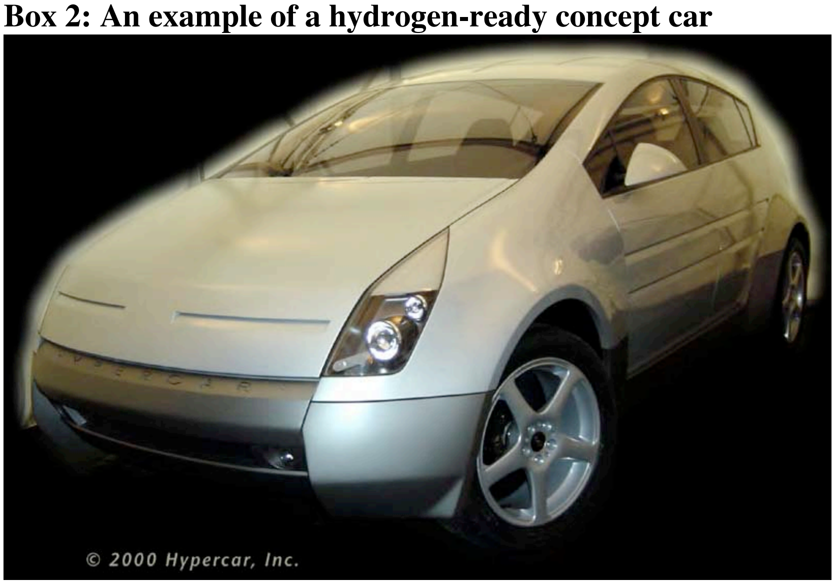
authorities, who have licensed 5,000-psi (~350-bar) hydrogen tanks, are expected to follow suit shortly. Linde AG recently installed a 700-bar German filling station for Adam Opel AG.[78]

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.

That factor shrinks still further — making the hydrogen tank only modestly bigger than a same-range gasoline tank in today's cars, but far lighter — when cars are designed to use two-thirds less power to move them, hence two-thirds less stored hydrogen for the same driving range. This requires cars with much lower aerodynamic drag, rolling resistance (energy losses to heating tires and road), and especially weight. Their weight can be halved, yet they can maintain superior crash safety even when hitting a heavy metal car, by making them from carbon-fiber composites. These space-age materials can absorb up to five times as much crash energy per pound as steel, and can crush more smoothly, using the crush length up to twice as effectively.

Carbon-fiber racecars are expensively handmade, but a new patent-pending manufacturing process[79] is expected to be affordable at automotive volumes (~10,000–100,000 cars per year). In 2000, its developer, Hypercar, Inc. — a technology development firm spun off from Rocky Mountain Institute in 1999 to commercialize lightweight and efficient vehicle technology — designed an ultralight concept car called the *Revolution* (see sidebar) to illustrate the implications of ultralight autobodies and highly integrated design. This conceptual midsize SUV would have the size, safety, comfort, and performance of a Lexus *RX300*, yet with five times its efficiency — a modeled average of 99 mpg equivalent.[80] Detailed production cost analysis suggests that such a concept car could be manufactured at mid-volume (~50,000/year) at a cost competitive with comparable-class vehicles in today's market.

Box 2: An example of a hydrogen-ready concept car



In November 2000, Hypercar, Inc. (www.hypercar.com) completed the virtual design and physical full-scale show-car construction (at left, with illustrative crossover design and "active outdoor lifestyle" styling) of its first concept car, the *Revolution*, representing one of many possible variants of a flexible, scalable platform. It is also production-costed and manufacturable. Developed on schedule and within budget, it met all its ambitious performance targets (below), which no established automaker has yet met in a single vehicle. The development effort was far faster and cheaper than industry norms. The design team also made encouraging progress in developing the vehicle's systems and subsystems, advancing solutions for composite-body manufacturing, and incorporating cost-effective proprietary manufacturing techniques to be validated in work currently underway.

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× Lexus *RX300* efficiency
- Goes 55 mph on just the power used by a normal car's air conditioner; its own air conditioner needs only ~1/5 that much power
- 0–62 mph (0–100 km/h) in 8.3 s; all-wheel digital traction control, responding far faster than today's ABS
- 330-mile / 530-km range on 7.5 lb / 3.4 kg of hydrogen safely stored in commercial 5-kpsi (350-bar) tanks
- Efficient packaging — 6% shorter overall and 10% lower than a similarly spacious 2000 Ford *Explorer*
- 47% of *RX300*'s curb mass (1,889 lb / 857 kg), but carries a similar load (1,014 lb / 460 kg), even up a 44% grade
- Low aerodynamic drag: $C_dA = 0.26 \times 2.38 = 0.62\ m^2$ (C_d from supercomputer simulation, not wind-tunnel)
- Emits only clean hot water; doesn't harm the earth's climate if fueled with sustainably sourced hydrogen
- Ground clearance from 5" / 13 cm at highway speed to 7.8" / 20 cm off-road, with unique suspension control choices
- Excellent aerodynamics; low-rolling-resistance tires ($r_0 = 0.0078$ on-road) can run flat for 125 miles (202 km) at 50 mph, requiring no spare
- Occupant safety cell undamaged in a 35-mph / 56 km/h simulated head-on wall crash—just replace the front end
- Designed to meet the Federal 30-mph / 48 km/h fixed-barrier occupant safety standard in a head-on collision *with a vehicle twice its weight,* each car moving at 30 mph (60-mph combined crash speed)
- Composite body doesn't dent, rust, or fatigue — bumpers bounce back unharmed from a 6-mph / 10 km/h collision
- Body ≥50% stiffer than a typical sports sedan (finite element analysis reported torsional stiffness of 38,490 Nm/deg, bending stiffness of 14,470 N/mm, first torsion mode of 62 Hz, and first bending mode of 93 Hz); this stiffness would be maintained by large-area adhesive bonding throughout the very long life of the vehicle, *vs*. metal autobodies' rapid loss of stiffness as spot-welds weaken or break
- Software-rich, open-architecture functionality offers numerous customization and upgrade paths
- Diagnostics, tune-ups, and upgrades performed via broadband wireless with many value-added options
- Highly redundant data systems and steer- and brake-by-wire controls increase safety
- Safety-enhancing, handicapped-friendly sidestick, sending the car in the direction in which you point it, automatically compensating for sidewinds, camber, and other outside influences; no hazardous steering column or pedals; safer driver airbag
- Very simple, intuitive driver display and controls; minimal driver distractions; automatic navigation to refueling sites
- Consistent with a 200,000-mile / 322,000-km warranty; lifetime brakes; repair shop visits should be rare

The platform combines uncompromised feature level and performance — a vehicle meeting and expanding expectations for functionality, esthetics, and environment — with strategically important advances in manufacturability, competitiveness, and profitability:

- Advanced-composite design and manufacturing processes tuned for new, affordable volume production methods
- No traditional body shop and no paint shop — traditional automotive assembly's two biggest costs
- A single worker can lift each body part unaided; body parts snap together in self-aligning, ultra-strong adhesive joints
- Far lower tooling and equipment cost, with modular manufacturing equipment investments phased as output grows
- Production-plant scale flexible downwards and modular upwards
- Potential for short product cycle times, supporting a diverse, agile, and rapidly evolving model portfolio
- Low breakeven volume and financial risk per model brought to market; more robust financial performance
- Financial risk/reward profile for manufacturers is therefore the opposite of the traditional car industry'

Such quintupled efficiency — in round numbers, threefold higher efficiency from the lighter and lower-drag platform, twofold from the fuel cell — should be broadly applicable to any other size and style of light vehicle. The two-thirds-smaller fuel cell would then become small enough to afford even at early prices — years earlier than would be possible with heavy, high-drag cars. Moreover, the two-thirds-smaller fuel tanks would become small enough to "package" (fit) conveniently, leaving plenty of room for people and cargo.

The *Revolution* would have a driving range of 330 miles with 137-L, 350-bar tanks holding 3.4 kg (7.5 lb) of hydrogen. That could be extended beyond 500 miles with the newer 700-bar tanks, which weigh and cost more and are slightly larger (because of their thicker walls) but hold two-thirds more hydrogen and are now assumed by many automakers. For comparison, 137 L (36 USgal) of gasoline would take an 18-mpg SUV like a 2000 Ford *Explorer* 650 miles, but not on one filling. Thus, depending on pressure, the 99-mpg *Revolution*'s 5.5-fold efficiency advantage over the *Explorer* makes its compressed hydrogen fuel only ~1.2–1.9 times bulkier than gasoline for the same range, not 9.6 times (the energy-content ratio of gasoline to 350-bar hydrogen). The smaller, easier-to-package fuel-cell powertrain further narrows that difference, so the *Revolution*'s interior spaciousness is comparable to the *Explorer*'s even though the *Revolution* is 10% lower and 6% shorter. This illustrates how superefficient, clean-sheet, whole-vehicle design can overcome the supposedly unsolved problem of onboard hydrogen storage. The claim here is only of an illustration, an existence proof: there may be other equally elegant design solutions. But the point is that though inefficient cars have hydrogen storage problems, efficient cars needn't.

Research continues on other storage methods — liquid hydrogen at –253°C or –423°F (favored by BMW[81] but costly, complex, and rather energy-intensive), heavy- or light-metal hydrides (low- or ambient-pressure but costly, heavy, requiring heat for release, and storing only a few percent hydrogen by mass), metal-organic frameworks,[82] even carbon nanotubes (which can hold a lot of hydrogen but don't readily let it go). So far, none comes close to beating the commercially available high-pressure tanks in weight or cost, and there is no volume or safety reason not to use those tanks in efficient cars. Further R&D on hydrogen storage is thus desirable but not essential.

Automotive high-pressure hydrogen tanks are filled in a few minutes via a small-diameter but rugged hose with a securely locking metal fitting, similar to those used to refuel with compressed natural gas. The hydrogen gas simply flows from a prefilled storage tank that's typically at about one-fifth higher pressure, like the self-contained Air Products Hydrogen Fueler with its 427-bar storage. Hydrogen refueling may become automated: it's no more suitable than is gasoline for dispensing by careless people, although even in the event of a mishap, the consequences would probably be less grave than with gasoline (Myth #2).

Myth #8. Compressing hydrogen for automotive storage tanks takes too much energy.

Compressing hydrogen to fill tanks to 350 bar using standard 93–94%-efficient intercooled technology takes electricity equivalent to about 9–12% of the hydrogen's energy content. However, most of that compression energy can be recovered aboard the car by reducing the pressure back to what the fuel cell needs (~0.3–3 bar) not with a throttling valve but with a miniature turboexpander 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 ~3–6% of the hydrogen's energy content. Further advances are emerging from other technologies, *e.g.*, in nonmechanical compression, such as the electrically-driven membrane technology developed by Canada's National Research Council.

Myth #9. Hydrogen is too expensive to compete with gasoline.

Onsite miniature[84] reformers made in quantities of hundreds, each supporting a few hundred fuel-cell vehicles[85] and using natural gas priced at a robust $5.69/GJ or $6/MBTU,[86] could *deliver* hydrogen into cars at ~$2.50/kg; with $3.79/GJ ($4/MBTU) natural gas, at ~$2.14/kg. (Of that, the cost of compression to ~500 bar, 50 kg of onsite storage, and dispensing into the car totals about $0.32/kg. All equipment is assumed to earn a 10%/y real aftertax return.)[87] For comparison, in cost per km for rather conventional fuel-cell cars nominally 2.2× as efficient as gasoline cars (both at LHV), U.S. untaxed wholesale gasoline at $0.90/U.S. gallon or $0.24/L is equivalent to $2/kgH$_2$; U.S. taxed retail gasoline at $1.35/U.S. gallon ($0.36/L), to $3/kg H$_2$.[88] (U.S. retail gasoline is cheaper than bottled water — which helps explain why many U.S. filling stations make more money selling soft drinks than gasoline.) Making more reformers would cut costs further. Relative prices differ in other countries — Europe and Japan, for example, typically pay more for natural gas— but they also tend to pay even higher gasoline prices, often equivalent to $8/kg H$_2$ or more so miniature reformers should retain their advantage abroad.

That advantage comes largely from avoiding the cost of hydrogen delivery, because miniature reformers use the natural-gas distribution system that's already been built. BP, Ford, and Accenture,[89] among others, have confirmed that hydrogen from natural gas can compete with gasoline in cost per km. This comparison is robust: hydrogen made in 20- or 180-nominal-car-per-day natural-gas reformers would have remained competitive with retail and wholesale gasoline, respectively, at the actual average prices of U.S. natural gas and gasoline for the past 22 years.[90]

Splitting water with electricity can seldom make cheaper hydrogen than reforming natural gas unless the electricity is heavily subsidized, bought at very low offpeak prices (usually well under 2¢/kWh)[91], or at very small scale (a neighborhood with a few dozen cars); that's why only a few percent of the world's hydrogen is now made electrolytically, powered mainly by old hydroelectric dams.[92] However, small-scale electrolyzers — now entering the market for demonstration and remote-location use — avoid the cost of hydrogen distribution from remote central plants, and in some circumstances they may compete with the decentralized gas reformers that offer the same advantage. Specifically, mass-produced (~1 million units) miniature electrolyzers, each serving a few to a few dozen cars, could produce hydrogen competitive with taxed U.S. gasoline even using 3¢/kWh offpeak electricity, so household-to-neighborhood scale could become a successful electrolysis niche market if enough units are made.[93] Yet such units, even initially using fossil-fueled electricity that might increase net carbon output per car (depending on the power 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 filling station). Homes in remote locations may also install LPG-reformer-based fuel-cell systems and use their reformers for the car too, avoiding trips to a faraway filling station.

While further analysis of these comparative investments is needed, it's encouraging that the head of Accenture's $2-billion-a-year global energy practice (since promoted) estimates a $280 billion U.S. investment in hydrogen fueling infrastructure, a surprisingly large $130 billion of it to convert filling stations — 26 times the estimate by Shell's former head of Group Planning[99] — plus $70 billion for natural-gas and ethanol supplies, $40 billion to move fuel to filling stations, and $40 billion for new pipelines. Her $280 billion estimate seems high. Yet she believes it would be "in line with what major oil companies already spend on petroleum exploration and production" — and could displace $200 billion in *annual* oil imports by 2020.[100]

Myth #11. Manufacturing enough hydrogen to run a car fleet is a gargantuan and hugely expensive task.

If all current global production of industrial hydrogen, about 50 million T/y, were fed into light vehicles about as efficient as the *Revolution* fuel-cell concept car described above (*i.e.*, quintupled-efficiency or "5η" for short), *it would displace two-thirds of today's entire worldwide consumption of gasoline*.[101] An estimated one-third of that hydrogen production is currently being used to *make* gasoline and diesel fuel;[102] the rest makes non-petroleum products. In the U.S., about half of all hydrogen is used by refineries, but highway-fuel consumption is also higher, so diverting all refinery consumption of hydrogen (~7 MT/y) into direct fuel for 5η light and 2η heavy vehicles would displace one-fourth of the gasoline (twice as much as comes from Persian Gulf oil), or one-seventh of the gasoline plus diesel fuel, used by all U.S. highway vehicles.[103] While making enough hydrogen to displace all U.S. highway vehicles' fuel is a significant undertaking, it looks reasonable in size and cost: it's comparable to the world's current total hydrogen production of ~50 MT/y, and just North and South Dakota have enough cost-effective windpower potential to make that much hydrogen.[104] (Byproduct oxygen could valuably gasify dry biomass or coal to make even more hydrogen.) Nor is the conventional hydrogen industry standing still: world hydrogen production is growing about 6% per year (particularly to help desulfurize diesel fuel), corresponding to a doubling every 11 years. Having fuel-cell car usage grow fast enough to outrun a hydrogen industry that's capable of such massive, but routine and invisible, expansion is a problem we'd love to have.

Myth #12. Since renewables are currently too costly, hydrogen would have to be made from fossil fuels or nuclear energy.

Hydrogen would indeed be made in the short run, as it is now, mainly from natural gas (particularly in North America), but when the hydrogen is used in fuel cells, total carbon emissions per mile would be cut by about half using ordinary cars, or by ~80+% using 5η vehicles.[105] That's a lot better than likely carbon reductions without hydrogen, and is a sound interim step while zero-carbon ways to produce hydrogen are being deployed.

Natural-gas prices would have to rise astronomically before electricity priced at just the *running* costs of *existing* nuclear power plants, plus electricity or hydrogen delivery costs, could compete with gas reformers sited at or near filling stations.[106] If this did occur, it might be a constructive 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[108] 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_2 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

billion on renewable energy R&D during 2003–06, mainly for hydrogen-related renewable sources. Solar cells, though currently much costlier than windpower (they cost ~8–30¢/kWh delivered to the customer), are growing even faster, and thanks to several recent technical breakthroughs, could approach ~5¢/kWh delivered in a decade or two — about competitive with the delivered cost of just *operating* existing nuclear plants, and ~2–3 times cheaper than new ones.

a. A hydrogen economy would require the construction of many new coal and nuclear power stations (or perhaps nuclear fusion stations).

This fear felt by many environmentalists is unfounded. New nuclear plants would deliver electricity at about 2–3 times the cost of new windpower,[111] 5–10 times that of new gas-fired cogeneration in industry and buildings, and 10–30+ times that of efficient use, so they won't be built, with or without a hydrogen transition. Any hydrogen produced from their electricity would be 4–7 times costlier in energy content, or about 2–3 times costlier per mile, than oil at the highest prices ever observed.[112] Further increasing nuclear power's cost disadvantage, often by as much as tenfold, are 207 "distributed benefits" of decentralized resources recently described by RMI.[113]

Under no conceivable circumstances would a market economy choose nuclear power. That's why it's dying of an incurable attack of market forces throughout the world, and why, reportedly, not a single investor showed up for its advocates' "nuclear revival" conference in Washington, DC on 11 September 2002. Proposed new types of nuclear fission (or fusion) plants would not change this conclusion, and would have other drawbacks, notably speeding the spread of nuclear-bomb-making materials. It is possible in principle to use nuclear heat rather than nuclear electricity to crack water to make hydrogen,[114] but this too can't compete with several other sources of high-temperature heat, including industrial byproduct heat and solar concentrators. And nuclear power is so slow to build that by the time new plants were licensed and built, renewable sources and other distributed resources would have completed their already rapid sweep of the market.

In short, electricity from today's cheapest sources is rarely competitive with natural gas for producing hydrogen. Nuclear electricity from existing plants, counting just their bare operating cost, is barely competitive with today's new gas-fired cogenerated electricity or windpower — even less so when hydrogen or electricity delivery costs are included — and doesn't even compete consistently with the operating cost of existing traditional fossil-fueled steam plants.[115] New nuclear plants are forever uneconomic; that's why the 2003 Senate energy bill includes $15 billion in new Federal loan guarantees (at an implied cost so high that private investment in the other half is highly implausible). Nor is the needed amount of hydrogen production particularly large (Myth #11). Finally, fuel cells make electricity that would become yet another devastating competitor to new and even existing nuclear plants. The hydrogen future, long advocated by nuclear enthusiasts as the savior of their failed technology, is just another nail in its coffin.[116]

b. A hydrogen economy would retard the adoption of renewable energy by competing for R&D budget, being misspent, and taking away future markets.

This concern is partly prompted by allegations — probably unprovable either way — that the Department of Energy may have diverted funds that Congress voted for renewable energy R&D into fossil-fuel hydrogen programs. Such diversion would be illegal and unwise. A similar real-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. Freedom-CAR 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) through electrolysis. Splitting the water and delivering the hydrogen will typically add far less cost than that higher price earns.
- A modest and cheap amount of local hydrogen storage can turn an intermittent source of electricity, such as wind or solar, into a firm dispatchable source that's far more valuable. (ICI in Britain has long stored very large amounts of hydrogen in underground caverns at up to 50-bar pressure without difficulty; Gaz de France has stored 50%-hydrogen town gas in large aquifers, as has the city of Kiel, Germany; and solution-mined salt caverns are known to be hydrogen-tight.[119] Helium storage in Texas rock strata beneath an aquifer offers another encouraging precedent.[120]) One of the world's leading experts on renewable energy, Professor Bent Sørensen of Roskilde University, notes that *all* of Denmark's energy — not just all of its electricity, a fifth of which now comes from wind — could be provided by windpower when lightly buffered with just two weeks of hydrogen storage, less than is now available in existing salt caverns. In larger countries, a considerable amount of hydrogen can be stored in the pipelines themselves ("linepack").

Both these features are especially valuable for renewables because of their flexible siting. Renewables also offer many other "distributed benefits" that can often increase their economic value by about tenfold.[121] But wouldn't nuclear power enjoy at least the first of the bulleted advantages? Yes. However, distributed alternatives and windpower cost even less than new nuclear plants, so they'd still win by a large margin — unless reforming natural gas beats them all.

Thus Assistant Secretary of Energy David Garman got it right when he wrote: "Over the long term, we want to make our hydrogen from sustainable, renewable energy, and that is where the majority of our hydrogen production R&D is focused.[122] But if environmental advocates persist 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

America), and is generally considered to have greater geological and economic abundance and to be less depleted than world oil. About 5% of U.S. natural gas was used in the mid-1990s to make industrial hydrogen[126] — probably nearer 8% today. Making enough hydrogen at typical miniature-reformer efficiency (~72%[127]) to run an entire year-2000 U.S. fleet of 5η light vehicles would take 20% of 2000 U.S. gas production.[128] More gas than that can be cost-effectively saved in the coming decades through efficiency improvements in buildings and industry.[129]

However, even without such gas savings, it is not obvious that switching light-vehicle fuel from oil-derived gasoline to natural-gas-derived hydrogen would increase the *net* consumption of natural gas significantly if at all. The sort of integrated hydrogen transition that RMI recommends,[52] and GM (among others) assumes, could even *decrease* net U.S. consumption of natural gas — by saving more gas in displaced power plants,[130] furnaces, and boilers, and in refineries to make gasoline than is made into hydrogen to displace gasoline. In other words, a well-designed hydrogen transition may reduce U.S. consumption of oil *and* natural gas *simultaneously*.

Conversely, anyone concerned about the views expressed at the June 2003 World Gas Conference about a U.S. trend toward greater domestic depletion and LNG import dependence should favor both the hydrogen transition — which would not materially burden gas reserves but could ultimately *save* natural gas by shifting hydrogen production to renewable sources or even carbon-sequestered coal — *and* efficient use of natural gas. Savings would emphasize coproduction of electricity and heat at all scales (U.S. power plants discard byproduct heat equivalent to 1.2× Japan's total primary energy use); thermally efficient buildings, hot-water systems, and industrial processes; and molecularly efficient materials cycles. For natural gas as for oil, the savings available from systematic thermal integration and end-use efficiency are huge and profitable, and can be vigorously pursued with or without a hydrogen transition. Two especially effective ways of saving North American natural gas in the short term would be to shave peak *electric* loads with efficiency, load management, and distributed generation[131] and to reward gas (and electric) distribution utilities for cutting customers' bills, not for selling more energy (as 48 states now do).

*Myth #13. Incumbent industries (*e.g.*, oil and car companies) actually oppose hydrogen as a competitive threat, so their hydrogen development efforts are mere window-dressing.*

Nearly all significant car and oil companies have vigorous R&D programs to explore hydrogen, and many have made multi-billion-dollar investments in the hydrogen transition. They don't do this for amusement; they're deadly serious, and expect to make money on it. In general, oil and gas companies can make more profit in a hydrogen economy than they do now, mainly because:

- hydrogen is a premium energy carrier, fetching a far higher price because it can do more work;
- it's generally more profitable and less risky to invest in natural gas than in oil;
- increasingly, hydrogen made from renewable energy sources can reduce or eliminate price volatility, which is more of a risk and cost than an opportunity to capital-intensive suppliers, and raises their cost of capital accordingly;
- hydrogen can be made near the customer, avoiding the need for costly and complex distribution infrastructure without necessarily giving up opportunities to participate in large-scale aggregated markets for technology, financing, and hydrogen services; and

- 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 U.S. filling stations as a highly competitive commodity at an untaxed wholesale price around \$0.90/USgal, equivalent to \$0.24/L, \$6.83/GJ (HHV), or \$7.39/GJ (LHV). To compete with this gasoline in cost per mile for a 2η, 3η, or 5η light vehicle, hydrogen (LHV) could bear a delivered untaxed price at the filling station of about \$1.77, \$2.66, or \$4.43 per kg, respectively. Yet the actual total cost of producing such hydrogen from \$3.79/GJ (HHV) natural gas — compressed, stored, and ready for dispensing into fuel-cell cars — is around \$2.1/kg if miniature gas reformers are produced in reasonable numbers (Myth #9).[133] Thus with a fuel-car car whose platform physics are only somewhat more efficient than in today's gasoline-engine cars (*i.e.*, 3η rather than a Hypercar®-level 5η), the potential retail markup of the hydrogen suggests that making even *oil*-based hydrocarbons into hydrogen, using existing and very competitive logistics for delivering liquid fuels to filling stations, might still undercut directly used gasoline because of hydrogen's more efficient end-use. In contrast, at a reasonable Kyoto trading price of, say, \$20/TC, carbon emissions avoided by displacing gasoline are worth only ~\$0.04/USgal — a few percent of the gasoline's retail price. Thus the hydrogen's efficient conversion to vehicular motion, not its climate-safety, is its main source of competitive advantage.

In practice, reforming delivered natural gas at the filling station is almost certainly cheaper than reforming oil-based products there, but the point of this illustration is rather that efficiently used hydrogen is far more valuable than cheap but inefficiently used gasoline. This suggests that if the cost of delivering hydrogen from relatively large oil-reforming plants can compete with that of distributed natural-as reforming, then we should be sending oil to reformers, not refineries.

Some analysts believe that in the next few decades, as methods of storing separated carbon cheaply and securely are proven, it will be cheaper still to extract hydrogen from coal, which contains less hydrogen than natural gas and is harder to handle, but is also far cheaper.[134] Some sequestration methods can also profitably reuse depleted oil and gas fields to store CO_2, turning these into an unexpectedly valuable asset for hydrocarbon companies providing sequestration services to the emerging negacarbon market.

Myth #14. A large-scale hydrogen economy would harm the Earth's climate, water balance, or atmospheric chemistry.

Water vapor does strengthen the warming effect of CO_2 by around 70%, and its climatic effects remain uncertain,[135] so this issue, like any other, must be carefully evaluated at the start of a proposed major shift in the energy system. Neglect of such prior technology assessment has proven very costly in the past. Fortunately, a sensibly designed hydrogen transition does not appear to present serious environmental issues if due attention is given to carbon releases.

a. Using hydrogen would release or consume too much water.

Other things being equal, a vehicle using hydrogen instead of a hydrocarbon will emit more water because it gets all its energy from hydrogen, whose use makes water, and none from hydrocarbons (coal, oil, gas, etc.), whose combustion makes water *and* CO_2. Location matters: the increased water emission may require liquid-hydrogen-fueled aircraft to fly below the stratosphere to avoid adding excessive contrails to its very dry air.[136] However, at least for cars, more efficient design can more than offset the extra water production: 5η fuel-cell-powered light vehicles would emit only half the water per mile of today's gasoline-engine equivalents.

The *source* of the hydrogen matters too. If the hydrogen were made from natural gas, then the oxygen would already have been in the air and the hydrogen would have come from underground, just like the hydrogen in crude oil. Morever, if the hydrogen were conventionally made in a steam reformer, then half the hydrogen would have come not from the methane but from the water; in this case, a 5η vehicle would emit only one-fourth as much *new* water per mile as its current gasoline-engine equivalent. And if the hydrogen were made by using electricity to split water, then all the water would already have been in the hydrologic cycle and would simply be returning to it. (The Department of Energy helpfully notes that "The hydrogen extracted from a gallon of water…could drive a hydrogen fuel cell vehicle as far as gasoline vehicles travel today on a gallon of gasoline."[137])

The Earth's atmosphere averages about 2.6% water by volume. This 13 trillion metric tons of water, cycling about every nine days, has very complex effects on climate, but as the following discussion shows, any net water that a hydrogen economy would add does not appear to be of concern. Most importantly, the climate benefit of removing light vehicles' CO_2 from the climate threat vastly outweighs any possible climate effect of 5η vehicles' or stationary fuel cells' water emissions.[138] The same holds for water consumption to the extent that the hydrogen comes from electrolysis; and of course that water is then re-created in the fuel cell.

For further perspective, the global energy system emits about 20 billion metric tons of water per year, roughly half "new" water from burning the hydrogen in fossil fuels and half existing water evaporated from power-plant cooling towers.[139] This total is equivalent to about 0.0038% of the Earth's annual water evaporation, or to roughly 1.7% of the atmosphere's annual *increase* in water vapor as it is warmed, mainly by heat-trapping caused by the CO_2 released by burning fossil fuels. (*Relative* humidity remains constant, so when the atmosphere is heated, absolute humidity rises.) Thus a fuel-cell car whose climate-safe hydrogen source emitted no CO_2 would reduce the water vapor added to the atmosphere by CO_2-induced warming by enormously more than it would directly add even in the worst case.

b. Using hydrogen would consume too much oxygen.

Regardless of the source of the hydrogen, its combination with oxygen in the fuel cell will not significantly change the atmosphere's content of oxygen, which is about 94 times as great as the amount of oxygen in atmospheric water. Burning fossil fuel combines oxygen with previously underground fossil carbon to form CO_2, of which roughly half is absorbed by the oceans, ultimately forming submarine rocks that remove the oxygen more or less permanently from the atmosphere. In contrast, hydrogen derived from fossil hydrocarbons releases less or no net CO_2

(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 been observed, and any hydrogen industry that leaked so badly would have serious problems of both safety and profitability.

How did the CalTech authors arrive at their assumption of 10–20% hydrogen leakage? They simply misread both of their references. The first[148], which clearly stated that the German hydrogen system loses 0.1% of its throughput, also offered as an example that a completely hydrogen-based global economy leaking 2–3% (and using no direct renewable energy) would emit about as much hydrogen as the fossil-fuel system emits now. A worst-case example was also presented that assumed 10% leakage for the sake of argument, although though it stated that 2–3% was more reasonable. The CalTech authors read all this to mean that the paper had "reasonably projected" a 10% leakage rate. They then claimed that "Losses during current commercial transport of H_2 are substantially greater than this, suggesting to us that a range of 10 to 20% should be expected." Where did they get the idea that "current commercial H_2 transport" losses exceed 10%? Remarkably, from a paper that said nothing whatever about such losses.[149] Its only quantitative estimates were for the daily boiloff rates of *liquid* hydrogen in small shipping containers (cryogenic truck and rail tankers). In fact, liquid hydrogen is only 10^{-3} of the world hydrogen market, boiloff is usually burned or otherwise reused rather than released, and any serious volumes of liquid hydrogen would be delivered via pipelines or large marine vessels[150] rather than small trucks; but apparently the CalTech authors overlooked all that. Due to the high cost of making and delivering liquid hydrogen, now used largely for space rockets, it will probably never compete economically in significant markets except aircraft, where hydrogen losses would be very low and hydrogen usage would be less than a tenth of the total market.[151]

Prior technology assessment is useful, indeed essential; this is simply not a good example of it. The CalTech authors concluded that, whatever its potential climate advantages from reduced CO_2 and other emissions, hydrogen leakage from a global hydrogen economy could considerably increase the risk to stratospheric dryness and photochemistry. This is incorrect because:

- They grossly overstated the hydrogen leak rates: instead of their assumed 10–20%, a more plausible estimate is at worst 1–2 percent, more likely a few *tenths* of a percent or less.[152] The authors do agree that hydrogen "emissions could be limited or made negligible, though at some cost," and no doubt the furore over their paper will help to focus attention on this issue, but they seem unaware that the hydrogen industry already achieves extremely low leakage as part of its normal operating practice and at modest cost, simply as a prudent strategy for public and asset protection.
- They didn't credit hydrogen for its greater end-use efficiency, enabling less hydrogen to deliver more service than can the fossil fuels it displaces.
- They didn't credit a hydrogen economy for reducing or eliminating most of the present causes of hydrogen emissions, which originate in fossil fuel and biomass usage. (Direct

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-range gasoline tank.[157] Such a vehicle therefore can't be as spacious as an equivalent fuel-cell car, but it could be significantly cheaper. One estimate at 20,000-unit production volume suggests ~$800–1,200 incremental cost for hydrogen-fueled internal-combustion-engine cars, or about $1,000–1,200 less than for 300,000-unit fuel-cell car production[158] — a difference that the fuel-cell vehicle's hydrogen savings would repay in 3–4 years from. For the same (300,000-unit) initial production volumes, the fuel cell car's incremental cost would drop to ~$480,[159] paying back in less than a year and a half. Such a first-cost advantage for the H_2-fueled engine hybrid is hardly compelling, and its lower fuel economy would make its fuel cost per km comparable to that of U.S. gasoline (~$0.36/L),[160] rather than less in the more efficient fuel-cell car. However, hydrogen-fueled engine-hybrid cars could temporarily help to hold a place for hydrogen in the market, and could achieve many of its major benefits to a large degree but sooner, while fuel cells are achieving mass production and low costs.[161] If such a car were also ultralight, that could help relieve its inherent design compromises, perhaps reducing the size penalty of the tanks from ~4× to ~2–3× (or taking part of the penalty in range), which may be acceptable for some markets. All these technologies should compete fairly, and big improvements may come in several successive steps. Even so, the ultralight-*plus*-fuel-cell platform's full benefits (Box 2, Myth #7), including the potential for such important value propositions as using parked cars as distributed electricity generators,[162] would certainly justify its relatively modest incremental cost.

c. We should improve batteries and increase the required electricity storage capacity (battery-electric driving range) of hybrid cars.

California has largely abandoned its mandate to introduce battery-electric cars because battery technology, as RMI predicted, was overtaken by hybrid technology, which will in turn be trumped by fuel cells. Battery-electric cars are a valid concept for niche markets, but (as Professor P.D. van der Koogh of the Delft University of Technology remarked) are "cars for carrying mainly batteries — but not very far and not very fast, or else they would have to carry even more 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. RMI is exploring ways to structure these transactions so that poor people, far from being deprived of affordable used cars, could afford to buy efficient new cars that they could then afford to run.

Oil productivity (dollars of real GDP per barrel of oil consumed) has doubled since 1975, yet that remarkable achievement has barely scratched the surface of how much efficiency is available and worth buying. The last time the U.S. paid attention to oil productivity, during 1977–85, Detroit improved new cars' efficiency by 7.6 miles per gallon in seven years. GDP rose 27%, oil use fell 17%, Persian Gulf oil imports fell 87–91%, and the halving of OPEC's exports broke its pricing power for a decade. Today we could do the same again, in spades.

A dozen years ago, the U.S. spent $61 billion to eject Iraq from Kuwait. Allies repaid all but $7 billion, equivalent to what a $1-per-barrel price hike costs Americans in less than a year. But for less than that $7 billion, Americans could have saved more oil than we import from the Persian Gulf. Similarly today, for enormously less investment than those lately committed in that region, the U.S. could switch to a combination of efficiency and non-oil fuels, chiefly hydrogen, that can rely on inexhaustible domestic resources and can make oil forever irrelevant to American mobility. (See Myth #19 below.)

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 vehicles could, in principle, enter production ramp-up as soon as 2007 with aggressive investment and licensing to manufacturers. Although the press frequently reports very long transition times as inevitable, and many in the auto industry understandably share that view, many experts feel the transition could be rather rapid. Accelerated-scrappage feebates (Myth #16) could turn over most or all of the U.S. car fleet in less than a decade. The handful of hydrogen refueling stations in Japan, Germany, and the United States could grow rapidly: Deutsche Shell has said hydrogen could be dispensed from all its German stations within two years if desired. However long the transition takes —which is matter of choice, not fate — it's better to start than not to, and we need to start quickly. The stakes are too high to dawdle.

Myth #18. The hydrogen transition requires a big (say, $100–300 billion) Federal crash program, on the lines of the Apollo Program or the Manhattan Project.

Many environmental and some political leaders are now proposing large, round numbers to symbolize the level of investment and commitment they consider appropriate. However, it's not at all clear that a Federal crash program is the right model when there's plenty of skill and motivation in the private sector to introduce hydrogen fuel-cell vehicles rapidly — if they can compete fairly. This is difficult when, for example, the latest tax law makes up to $100,000 for buying a *Hummer* (ostensibly for business purposes) deductible in new tax breaks, federal funds for automotive innovation virtually exclude innovation-rich small businesses, global and state initiatives to make carbon costs visible are opposed by the federal government, and feebates aren't yet on the agenda (disadvantaging American businesses). Incoherence in automakers' strategy is also undercutting their impressive innovations — trumpeted in full-page ads about their hydrogen cars — with contradictory marketing or litigating messages that hydrogen is far off and impractical (as they must presumably claim in their suit to oppose California's proposed CO_2 regulations) or that efficient cars must be small and unsafe (as they did claim when lobbying against tighter car-efficiency standards).

Coherent private- and public-sector policy could go a long way toward a rapid and profitable hydrogen transition. There are signs of smarter policy emerging in the Department of Energy's recent restructuring to integrate hydrogen, vehicle, building, and utility programs. On the other hand, a senior DOE official, when told in January 2002 that the just-announced FreedomCAR program hoped to develop over the next 10–20 years a car that had already been designed in 2000, replied, "Well, then, we'd better not try to help you, because we'd just slow you down." That might be true, but it shouldn't be true, and if we want a vibrantly competitive rather than a failing automotive industry, we'd better make it as untrue as possible.

The total cost of a hydrogen transition is probably a lot more than the $1.7⁺ billion proposed by President Bush over the next five years, but it is probably far less than $100–300 billion. It may not be much bigger than the billions of dollars that the private sector has already committed to pieces of the puzzle — if the money is intelligently spent on an integrated buildings-and-vehicles 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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Notes

1 J. Ball, "Skeptics: Fuel Cells a Long Shot," *Wall St. J.*, 30 Jan. 2003.
2 *Wall St. J.* editorial, "Hydrogen Car Hype," 30 Jan. 2003.
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4 G. Easterbrook, "Car Talk: Why Bush's h-car is just hot air," *New Republic* **4597**:13–15, 24 February 2003.
5 B. Eliasson & U. Bossel, "The Future of the Hydrogen Economy: Bright or Bleak?," *Procs. Fuel Cell World* (Luzern), 1–5 July 2002, pp. 367–382, European Fuel Cell Forum (Morgenacherstr. 2F, CH-5452 Oberrohrdorf, Switzerland), posted at www.methanol.org/pdfFrame.cfm?pdf=HydrogenEconomyFinalReport.pdf, www.evworld.com/databases/storybuilder.cfm?storyid=471, and www.woodgas.com/hydrogen_economy.pdf.
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7 L. King, "Stealing the environmental Holy Grail," *Tallahassee Democrat*, 2 Feb. 2003, p. E1.
8 D.E. Knoll, "Hydrogen Pipedreams," *Wall St. J.* letter, 13 March 2003.
9 T. & R. Magliozzi (The Car Guys), "Hydrogen cars still way off," *The Denver Post*, p. 3F, 10 March 2003.
10 D. Morris, "Second Thoughts on a Hydrogen Economy," *AlterNet*, 24 Feb. 2003, www.ilsr.org/columns/2003/022403.html.
11 P. Schwartz & D. Randal, "How Hydrogen Can Save America," *Wired* **11.04**:5–13, April 2003, www.wired.com/wired/archive/11.04/hydrogen.html.
12 United States Council for Automotive Research (U.S.CAR), "Hydrogen as a Fuel," www.uscar.org/Media/2002issue2/hydrogen.htm, downloaded 14 March 2003.
13 Many people who should know better get this wrong. Even ExxonMobil Chairman Lee Raymond, in a talk prepared for the World Gas Conference in Tokyo on 3 June 2003, reportedly called hydrogen an energy "source."
14 A good lay summary of the alternative methods is at pp. 19–22 of B. Kruse *et al.*, *Hydrogen — Status and Possibilities*, Bellona Foundation report 6–2002, Oslo, 2002, www.bellona.no/en/energy/hydrogen/report_6-2002/index.html. The theoretical energy needed to split water at 25°C is 1.23 eV, today's electrolyzers run at ~1.7–1.9 eV, and 1.9 eV corresponds to a visible red wavelength of 650 nm, so "the entire visible spectrum of light has sufficient energy to split water into H_2 and O_2"; the key is finding an efficient and affordable catalyst. J.A. Turner, *Science* **285**: 687–689 (30 July 1999), at n. 12.
15 In Greek, "hydrogen" means "water creator."
16 See ref. 3.
17 The Lower Heating Value of 1 kg of hydrogen (the value appropriate for use in a fuel cell) is 98.6% of the corresponding LHV of gasoline (115,400 BTU/USgal), or 91% of the Higher Heating Value of gasoline (125,000 BTU/USgal). See note 18.
18 The author often erroneously did the same for hydrogen in the 1970s and early 1980s, and many analysts still do. A smaller but also significant distinction must also be drawn in how energy content is measured for different fuels.

This article expresses hydrogen's energy content at its Lower Heating Value (LHV), 120 MJ/kg, as is appropriate for low-temperature fuel cells. Hydrogen used in a condensing boiler or furnace can yield 18% more energy (the Higher Heating Value or HHV, 142 MJ/kg) because the difference — the latent heat of vaporizing the resulting water into steam — can also be recovered. Natural-gas and gasoline energy content and prices, by convention and in this article, are normally expressed at HHV. At the point of end-use, however, HHV is usually applied only to condensing boilers and furnaces that can recover the energy of condensing steam back into water, while LHV is commonly used for engines, gas turbines, power stations, and fuel cells.

[19] Lower figures, around 50% or somewhat less, are sometimes quoted for suboptimally designed systems, particularly those crammed into small volumes and fed with air from inefficient blowers.

[20] The Otto (normal gasoline piston) engine is 30-odd percent efficient under ideal conditions, but having to operate over a wide range of speed and torque cuts its average as-used efficiency about in half.

[21] The Otto engine is most efficient under its highest loads, which very seldom occur: most of the time, the car uses only a small fraction of the engine's capacity (about a sixth in highway cruising or a few percent in city driving). In contrast, fuel cells are most efficient at the low loads that dominate automotive operation. Thus the fuel cell is inherently better matched than an Otto engine to the car's varying loads. Engine-hybrid drive reduces the fuel cell's advantage, although hybridizing the fuel cell too can partly recover that loss.

[22] J.N. Swisher, *Cleaner Energy, Greener Profits*, RMI, 2002, www.rmi.org/images/other/E-CleanerGreener.pdf. A well-known example is a large Omaha credit-card processing center whose redundant fuel-cell power supply avoids costly power failures from the grid. Fuel cells also produce direct current, which can be used directly in digital equipment rather than converting it to alternating current and back: see the report of Rocky Mountain Institute's February 2003 San Jose charrette on superefficient data-center design, www.rmi.org/sitepages/pid626.php.

[23] Hydrogen Information Network, www.eere.energy.gov/hydrogenandfuelcells/hydrogen/faqs.html.

[24] At the Lower Heating Value of gasoline (see note 18).

[25] Since the density of hydrogen gas at standard conditions is 0.090 kg/m^3, a kilogram of H_2 occupies 11.1 m^3. One cubic meter equals 35.3 cubic feet. Naturally, the amount of any gas in a cubic meter depends on its pressure, which is conventionally measured under "standard" or "normal" conditions — 100,000 Pa (0.987 bar) pressure and 273.15 K (0°C) — though slightly different conditions are sometimes assumed.

[26] See note 23.

[27] The best information RMI has so far found indicates ~2002–03 U.S. use of ~15 MT/y of hydrogen (note 29), equivalent to not one-fifth but one-third of the commonly quoted ~50 MT/y of global hydrogen use.

[28] The reformer's catalytic process heats the methane, partially oxidizes it to carbon monoxide, reacts that with steam to "shift" to a mixture of hydrogen and carbon dioxide, then separates them, typically using amines. It is often followed by a further cleanup stage, such as pressure-swing adsorption, depending on the hydrogen purity desired. The overall reforming/shift reaction turns one molecule of methane (CH_4) and two of water (H_2O) into four molecules of hydrogen (H_2) and one of carbon dioxide (CO_2). The hydrogen comes half from the methane and half from the water. Reformation is similar for larger hydrocarbon molecules, and is endothermic, requiring heat to be added. The shift reaction is exothermic, but at a lower temperature, so instead of directly reusing the heat, engineers normally use separated and cleaned-up shift-reactor tailgas to fuel the reformer.

[29] Published recent data on global hydrogen uses by sector or end-use are hard to find, there is no official data source or public hydrogen market, many data are proprietary, data differ markedly between leading hydrogen companies, firms' published data may differ from their internal "what-we-believe" data, many data are poorly specified, and many data sets are fuzzy or incomplete (so Air Products says total and refinery usage of hydrogen is uncertain to ±15%). Nonetheless, an approximate picture can be pieced together. **World:** The 37%-to-refineries fraction, apparently around the mid-1990s, is a low-end estimate from David Hart (Imperial College, London), *Hydrogen Power — The commercial future of 'the ultimate fuel,'* Financial Times Energy Publishing, 1997, p. 71, Table 5.3, Hydrogen consumption by industry (also showing 50% going to produce ammonia and 8% to produce methanol); it's also quoted by the IEA (www.ieagreen.org.uk/h2ch2.htm) in 1999 and as Fig. 7 of Kruse *et al.* (ref. 14) in 2002. In contrast, data presented at the Hannover Messe in 2003 by Air Liquide (kindly provided by Bjørner Kruse) states that world H_2 production in 2001 was 540 billion m^3 (equivalent to 48.6 MT/y), going 51% to ammonia, 45% to refining (including 6% "over-the-fence"), 3% to chemicals (3% OTF), and <1% to others (57% OTF). This 37–45% range is probably due partly to the different date and partly to different conventions for counting or excluding refineries' byproduct hydrogen as discussed below. **United States:** The *Chemical Economics Handbook* lists 1999 U.S. hydrogen consumption as 3.152 trillion standard cubic feet (Tscf), equivalent to 8 MT/y and reasonably consistent with the U.S. Department of Energy website's undated "9 million tons" per year

(www.eere.energy.gov/hydrogenandfuelcells/hydrogen/hydrogen_feature.html, probably using short rather than metric tons) or "over 90 billion cubic meters" or 8.1 million metric tons per year (MT/y) (www.eere.energy.gov/hydrogenandfuelcells/hydrogen/current_uses.html). *CEH* says the usage comprises 88% captive users (38% ammonia, 37% refineries, 10% methanol, 4% other) and 12% merchant users (11.2% pipeline or onsite, 0.8% cylinder/truck/rail). However, much of the merchant use goes to the same usage categories already separately listed in the "captive" category: Air Products data, for example, indicate that 1.1 Bscf/d, or 29% of "on-purpose" usage, by U.S. refineries in 2001 was outsourced, while a further 2.7 Bscf/d was insourced. In 1999, therefore, the *CEH* data indicate that U.S. refineries used 1.164 Tscf of captive-market hydrogen plus an unstated amount of merchant hydrogen. A separate recent estimate says 67% of U.S. merchant hydrogen went to refineries and another 26% to petrochemical plants (C.E. Thomas, pers. comm., 3 March 2003), implying total refinery usage of ~1.417 Tscf/y in 1999, or 45% of total U.S. hydrogen usage as given by *CEH*. For ~2002–03, Air Products puts refinery usage at ~47% of an 84% higher figure for total U.S. hydrogen consumption: 16 Bscf/d or ~5.8 Tscf/y (15 MT/y, 1.8 EJ/y). Fuller data kindly provided by Air Products — the world's biggest merchant hydrogen producer, at over 0.9 Bscf/d — suggest that the *CEH* data may be understating both refinery and total U.S. hydrogen usage by not fully reflecting refineries' onsite byproduct hydrogen production. (Such an omission would account for 55% of the discrepancy in total U.S. hydrogen usage; the rest could come from omitting similar internal and byproduct hydrogen streams in other industries.) The Air Products data show that U.S. refineries' 2001 production and consumption of hydrogen totaled ~7.5–8 BscfH_2/d, with the range depending on purity (T.C. Golden, pers. comm. to Ken Robinson, 10 April 2003, and K.M. Campbell (Global Mktg. Mgr., Air Products), pers. comm., 20 June 2003). Of this total, ~3.8 Bscf/d is "on-purpose" hydrogen and the other ~4 Bscf/d is ~75–93% pure byproduct hydrogen produced by catalytic reformers used to make high-octane gasoline (via dehydrocyclization, which converts straight-chain paraffins to aromatics). This makes it appear that slightly over half of U.S. refinery hydrogen is absent from the *CEH* statistics because it's an internal process flow. Air Products estimates that some ~10–15% of the ~7.5–8 Bscf/d total ends up in refinery fuel rather than in products, but refinery H_2 is growing rapidly (by 32% during 1991–2001; 84% of that growth was outsourced, typically because demand for high-quality, low-sulfur fuels outran the aromatics-byproduct hydrogen made onsite). Roughly netting the growth and the usage as refinery fuel, we can therefore reasonably assume for ~2003 the lower end of the 2001 range, ~7.5 Bscf/d of U.S. refinery usage, equivalent at a nominal 100% duty factor to 2.74 Tscf/y — 2.35 times the apparently-low *CEH* captive-user figure for 1999. At a conventional LHV conversion of 35.3 scf/Nm^3 [N ≡ normal], 10.8 MJ/Nm^3, and 120 MJ/kg, 2.74 Tscf/y is equivalent to 7 MTH_2/y of total refinery hydrogen with an energy content of 0.84 EJ/y. The continuing growth in refinery usage is due to higher light-product yields, more-sour crudes, and tighter desulfurization specifications: Air Products expects hydrogen usage to rise further, from 400–800 scf/bbl for typical U.S. refineries in the 1990s (to achieve <1,000 to <30 ppm S) to 800–1000$^+$ scf/bbl in ~2010$^+$ (to achieve <15 to <30 ppm S). (As a consistency check, U.S. refineries processed 16.31 Mbbl/d of crude oil in 2001, so ~7.8 Bscf/d of H_2 would be equivalent to 478 scf/bbl, well within the 1990s range stated.) RMI's efforts to refine these data are continuing.

[30] "Hydrogen Pipelines," HyWeb, 18 Dec. 2002, Ludwig-Bölkow-Systemtechnik GmbH (LBST) / German Hydrogen Association, www.hydrogen.org/News/arcv402e.html#LBST%20Analysis%2002-12-18, updated by B. Kruse *et al*. (ref. 14), p. 28.

[31] W.C. Leighty, M. Hirata, K. O'Hashi, H. Asahi, J. Benoit, & G. Keith, "Large Renewables–Hydrogen Energy Systems: Gathering and Transmission Pipelines for Windpower and other Diffuse, Dispersed Sources," World Gas Conf. 2003 (Tokyo), 1–5 June.

[32] Air Liquide, "Hydrogen Delivery Technologies and Systems," *Procs. Hydrogen Delivery Workshop,* www.eere.energy.gov/hydrogenandfuelcells/hydrogen/wkshp_h2_delivery.html, 7–8 May 2003, Sandia National Laboratories.

[33] "Hydrogen Liquefaction," HyWeb, 28 Feb. 2003, LBST/GHA, www.hydrogen.org/News/arcv103e.html#LBST%20Analysis%2003-02-28.

[34] See www.hydrogenus.org/, www.eere.energy.gov/hydrogenandfuelcells/codes/, and www.eere.energy.gov/hydrogenandfuelcells/codes/pubs.html. It follows that the risks of wide public deployment are comparable to or less than those of the existing wide public deployment of other fuels, including gasoline. However, historic doctrines governing tort liability may not adequately recognize this: R. Moy, "Liability and the Hydrogen Economy," *Science* **301**:47 (4 July 2003), www.sciencemag.org/cgi/reprint/301/5629/47a.

[35] This is true also for hydrogen evaporating from a spill of liquid hydrogen, which is not directly flammable. Thus a liquid spill of 3.3 m^3 in a 4 m/s wind has a danger zone of 1,000 m^2 for hydrogen, 5,000 m^2 for methane (LNG), and 13,500 m^2 for propane, and of those three gases, only hydrogen cannot form a "fire carpet." R. Faaß, "Cryoplane:

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.*, *On the Road in 2020: A life-cycle analysis of new automobile technologies*, MIT EL 00-003, 2000, at p. 2-5, http://lfee.mit.edu/publications/PDF/el00-003.pdf, updated in 2003 by M.A. Weiss *et al.*, *Comparative Assessment of Fuel Cell Cars*, http://lfee.mit.edu/publications/PDF/LFEE_2003-001_RP.pdf.

[43] Thomas (*op. cit. infra*, ref. 53) uses a nominal value of 72% (LHV hydrogen produced / LHV natural gas input), not counting minor use of electricity by the miniature reformer.

[44] Boeing's exothermic One-Step Hydrogen (BOSH) process, now in testing, is predicted to be even more efficient, and to cost half as much as traditional reformers. Other developers are on similar trails.

[45] Or ~80–90+% for electrolyzers using hydrogen's Higher Heating Value. R. Wurster & W. Zittel (LBST), "Hydrogen Energy," *Procs. Workshop on Energy Technologies to Reduce CO_2 Emissions in Europe: Prospects, Competition, Synergy,* Energieonderzoek Centrum Nederland (ECN), Petten, 11–12 April 1994, www.hydrogen.org/Knowledge/ECN-h2a.html. At low load, which correspondingly decreases asset utilization, the HHV efficiency can be much higher yet: for example, Hans Hoffman of the German firm GHW (pers. comm., 17 March 2003) reports 82% (HHV) at full load, rising to 98% at 1/6 load, measured for the 450-kW, 30-bar alkaline electrolyzer at the Munich airport.

[46] See note 18.

[47] Toyota Motor Corporation, slide "Well to Wheel Efficiency," using Japanese 10–15 test mode (other countries' test procedures differ) and Toyota's fuel-cell vehicle target, presented to Shanghai Fuel Cell Vehicle Forum, 4–5 December 2002. Current fuel-cell cars are slightly less efficient than this target because many still have powertrain efficiencies (tank-to-wheels) nearer 50% than 60%. The U.S. version of the GM/Argonne well-to-wheels analysis is generally less sanguine than Toyota's expectations because of its unnecessarily conservative assumptions about vehicle design. The European variant (ref. 142) turned out somewhat better, partly due to a more advanced transmission and a more efficient natural-gas supply system. Both studies found that direct-hydrogen fuel-cell vehicles offered the greatest advances in fuel savings and climate safety.

[48] W. Zittel & R. Wurster (LBST), "The prospects for a hydrogen economy based on renewable energy," *Procs. Conf. Ireland's Transition to Renewable Energy*, 1 Nov. 2002, www.hydrogen.org/Knowledge/Ireland2002.html.

[49] However, well-designed big liquefaction plants could reduce the electricity input to as little as 21% of the liquid hydrogen's energy content (ref. 33). Some newer technologies such as magnetic or sonic cooling, or thermionic quantum tunneling diodes (www.coolchips.com), may improve this further. The liquefaction energy can also be recovered to provide cooling at the site of regasification, as is sometimes done with liquefied natural gas, which is at about –161˚C (*vs.* liquid hydrogen's –253˚C).

[50] Liquid hydrogen contains one-fourth the energy of kerosene per gallon but is 2.8 times lighter per unit of energy, permitting ~20–25% higher payloads (ref. 48): aircraft designers care far more about weight than volume. It also burns far cleaner: instead of 1 kg of kerosene making 3.16 kg of CO_2 and 1.24 kg water plus CO, soot, NO_x, SO_2, and unburned hydrocarbons, 0.36 kg of hydrogen (with identical energy content) makes 3.21 kg of water, traces of NO_x (if burned in a jet engine, not if used in a fuel cell), and nothing else. Actual LH_2 usage and emissions would be less because hydrogen's mass, drag, climb, cruise, and engine-efficiency effects (for a nominal 767 platform) yield a ~10–15% net gain in fuel economy: D. Daggett (Boeing), "Commercial Airplanes: Hydrogen Fueled Airplanes," Hydr. Prodn. & NW Transportation Conf., Seattle (PNL), 16 June 2003, and pers. comm., 16 June 2003. NASA, Boeing, and Tupolev have done liquid-hydrogen aircraft design studies; a Tu-154 flew on liquid hydrogen fuel in 1988. Airbus's 35-partner consortium (www.diebrennstoffzelle.de/h2projekte/fahrzeuge/cryoplane.shtml), under EU funding, has already established the concept's basic feasibility and safety. (Kruse *et al.*, ref. 14, also cited at p. 48 a pair of U.S. studies showing that in a crash, a liquid-hydrogen passenger jet would be safer than a kerosene-fueled one.) Boeing has announced work on fuel-cell applications for both propulsion and auxiliary power, and expects in

2003 to flight-test an experimental one-seat aircraft with propellers driven by a 25-kW fuel cell after battery-boosted takeoff (W. Knight, "Fuel cell-propelled aircraft preparing to fly," 12 May 2003, www.newscientist.com/news/print.jsp?id=ns99993717).
[51] Assistant Secretary of Energy David Garman correctly, if somewhat conservatively, states that "a fuel-cell vehicle vehicle using hydrogen produced from natural gas uses 50% less energy and emits 60% fewer greenhouse gases compared to a gasoline vehicle" (assuming the vehicles are identical except in powertrain and fuel): "Freedom Car: 'Free Ride' or Fuel Economy Savior? An e-FFFIENCY NEWS Point-Counterpoint," Alliance to Save Energy newsletter, 21 May 2003, www.ase.org. His source is a standard A.D. Little–DOE 2002 study summarized in DOE's Feb. 2003 fuel-cell report to Congress, ESECS EE-1973, at www.eere.energy.gov/hydrogenandfuelcells, p. 3.
[52] A.B. Lovins & B.T. Williams, "A Strategy for the Hydrogen Transition," *Procs. Natl. Hydr. Assn. Ann. Conf.*, April 1999, www.rmi.org/images/other/HC-StrategyHCTrans.pdf.
[53] C.E. Thomas, "Hydrogen and Fuel Cells: Pathway to a Sustainable Energy Future," 2 February 2002, www.h2gen.com/main.php?page=why.html.
[54] C.E. Thomas, personal communication, 4 June 2003.
[55] See ref. 52.
[56] This reduction, based on the actual car design described below, is larger than the official ~40-67% range normally cited, because it assumes a car whose lighter weight and lower drag greatly reduce the power needed to propel it.
[57] This is mainly an issue for coal because it is most of the global fossil-fuel resource and has the highest carbon/hydrogen ratio of all fossil fuels. Technologies now known or being explored for sequestering carbon do not look promising for decentralized use of coal, but some do show promise for centralized use of coal.
[58] However, *marine* transportation of liquid hydrogen, though not mentioned by the Swiss authors, may well make economic sense (just as liquefied natural gas is increasingly transported today), but would be safer than LNG. Large, perhaps fourfold, increases in the energy efficiency of conventional large-scale LNG production are feasible and probably profitable in new installations, and similar opportunities would apply to LH_2 plants.
[59] Some of the largest U.S. refineries today are earning more profit as merchant electricity producers than as refiners of petroleum products. The opportunity to earn more money by selling merchant hydrogen than hydrocarbons is analogous.
[60] See ref. 30.
[61] See ref. 32.
[62] *Id.*
[63] See refs. 31–32.
[64] "Hydrogen Distribution using Low-pressure Gas Pipelines," HyWeb, 25 Oct. 2002, LBST/GHA, www.hydrogen.org/News/arcv402e.html#LBST_Analysis_02-12-18.
[65] B.J. Feder, "For Far Smaller Fuel Cells, a Far Shorter Wait," *New York Times*, 16 March 2003, www.nytimes.com/2003/03/16/business/yourmoney/16FUEL.html.
[66] J.N. Swisher, *op. cit. supra*, ref. 22.
[67] For example, properly arranged fuel cells can provide a microchip fabrication plant with seven benefits — ultra-reliable power, displacement of the capital and maintenance cost and the ~6–8% losses of the uninterruptible power supply, process heat, ultra-pure hot water (a costly process input), and onsite hydrogen production that can also displace process hydrogen currently imported in tube trucks. Together, these benefits usually justify a prompt retrofit. Similarly, Dow and GM plan to start testing in late 2003 and deploying in 2006 up to 35 MW of PEM fuel cells into Dow's biggest plant — the 30-square-mile, ~1,750-MW Freeport complex in Texas — to turn chloralkali-byproduct hydrogen into direct-current electricity (good for electrochemistry) and useful heat: Dow press release "Dow Plans to Use GM Fuel Cells in World's Largest Fuel Cell Transaction," 7 May 2003, www.dow.com/dow_news/corporate/2003/20030507c.htm.
[68] For this reason, no serious student of the subject expects any problem with availability of the platinum-group catalyst metals, whose requirements should be comparable to those of existing cars' catalytic converters if well-designed stacks use direct hydrogen. The value of even low catalyst concentrations, however, will probably encourage leasing, lifecycle responsibility, or other business models that encourage complete catalyst recovery at the end of the stack's working life.
[69] PEM, which can mean (identically) Proton Exchange Membrane or Polymer Electrolyte Membrane.
[70] L.D. Burns, J.B. McCormick, & C.E. Borroni-Bird, "Vehicle of Change," *Sci. Amer.*, pp. 64–73, Oct. 2002. The gain in power density since 1989 exceeds 20-fold: T. Lipman & D. Sperling, "Market concepts, competing tech-

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.
[76] J.M. Ogden, R.H. Williams, & E.D. Larson, "Societal lifecycle costs of cars with alternative fuels/engines," *En. Pol*., 2003, in press.
[77] Some, chiefly in the methanol industry, dispute claims of MTBE's toxicity and blame its California demise on the ethanol lobby. Whatever the scientific reality, wide retention and adoption of MTBE faces serious political hurdles.
[78] "Linde has created filling station using 700-bar technology for the Adam Opel AG," *HyWeb—Gazette*, 2Q2003, www.hyweb.de/gazette-e/. According to G. Thomas & J. Keller, "Hydrogen Storage — Overview," *Procs. Hydrogen Delivery Workshop,* www.eere.energy.gov/hydrogenandfuelcells/hydrogen/wkshp_h2_delivery.html, 7–8 May 2003, Sandia National Laboratories, p. 6, such tanks raise the H_2 LHV energy density from 2.7 MJ/L at 350 bar to 4.7 MJ at 700 bar — less than a doubling because of departures from the Ideal Gas Law. The corresponding system densities, including tank and its immediate fittings, are about 1.95 and 3.4 MJ/L. For comparison, liquid hydrogen has an estimated storage density of 4.2–5.6 MJ/L (*id*.).
[79] Hypercar, Inc.'s AVACS™ (Automotive Volume Advanced Composites Solution) is described in D.R. Cramer & D.F. Taggart, "Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure," *Procs. 19th Intl, Battery, Hybrid & Fuel Cell El. Veh. Sympos. & Exh*., Seoul, 2002 (EVS-19), www.hypercar.com/pdf/Hypercar_EVS19.pdf.
[80] The *Revolution* concept car by Hypercar, Inc., www.hypercar.com/pages/casestudies.html. See A.B. Lovins & D.R. Cramer, "Hypercars®, Hydrogen, and the Automotive Transition," *Intl. J. Veh. Design*, special future-vehicles issue, in press, 2003.
[81] For reasons obscure to other automakers, BMW has demonstrated both liquid-hydrogen fueling and its use only for auxiliary power, not for propulsion. On 9 April 2003, GM announced a joint development program with BMW for liquid hydrogen refueling devices, which have some adherents in Germany under draft specifications by the European Integrated Hydrogen Project. GM seeks global standardization on a LH_2 refueler coupling in case liquid hydrogen proves unexpectedly attractive, but its own development is strongly oriented toward gaseous hydrogen.
[82] N.L. Rosi *et al*., "Hydrogen Storage in Microporous Metal-Organic Frameworks," *Science* **300**:1127–1129 (16 May 2003), summarized in M.D. Ward, "Molecular Fuel Tanks," *Science* **300**:1104–1105 (16 May 2003).
[83] L.C. Moulthrop, Jr., VP Product Development, Proton Energy Systems, personal communication, 12 May 2003.
[84] Bigger than home-scale, but far smaller than the currently prevalent industrial scale.
[85] An average U.S. gasoline filling station refuels ~175 cars/day, each at an average interval of ~8 days. An equivalent hydrogen station would support ~1,400 fuel-cell cars — or more if they're unusually efficient.
[86] Most gas experts agree that a commercial gas price of ~$6/GJ should be ample to ensure supplies for a very long time, even in currently gas-short North America.
[87] C.E. Thomas, personal communication, 4 June 2003.
[88] Thomas (ref. 53). The 2.2η assumption is also from his extensive analyses with and for Ford, is empirically grounded in conventional fuel-cell technology, and assumes only modest reductions in mass and drag. The variable-cost economics are straightforward. An 85%-efficient reformer converts, say, $4/GJ HHV or $4 × 1.11 = $4.44/GJ LHV natural gas into $4.44/0.85 = $5.22/GJ LHV hydrogen, or $0.63/kg. With 75% (LHV) electrolyzer efficiency, since 1 kWh contains 3.6 MJ, $0.02/kWh yields $7.4/GJ or $0.89/kg hydrogen — the equivalent of $5.67/GJ (HHV) natural gas. The electrolyzer is also about twice as capital-intensive if both units are at industrial scale (Wurster & Zittel, *op. cit. supra,* ref. 45), and normally has costlier transmission and distribution infrastructure, although this can shift if the gas grid is full even at off-peak periods but the electric grid is not.

[89] M. Tolan, "Innovative Visions — Art of the Possible: Potential for Dramatic Energy Mix Shift," Accenture International Utilities and Energy Conference (Aventura, Florida, 24 March 2003); R. King, "Mary Tolan's Modest Proposal," *Business 2.0,* June 2003, pp. 116–122, http://www.business2.com/articles/mag/0,1640,49464,00.html.
[90] See ref. 53.
[91] Where off-peak electricity is cheap enough for electrolysis to compete with gas reformers, the price of off-peak electricity may come to be driven by the market for hydrogen, while the on-peak market would be driven by demand for electricity.
[92] However, electrolytic hydrogen may well compete with gasoline in countries like Iceland or Norway, where hydropower is cheap while gasoline is heavily taxed.
[93] See note 88.
[94] DOE, Office of Hydrogen, Fuel Cells, and Infrastructure Technologies, 3 June 2003 draft multi-year program plan, www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.1_production.pdf.
[95] *E.g*., Thomas & Keller, ref. 78. However, the nature of the impurity matters — sulfur, for example, can cumulatively poison the catalyst, while the effects of carbon monoxide are generally reversible — and there are complex tradeoffs between lifetime, efficiency, cost, and hydrogen purity.
[96] L.D. Burns, J.B. McCormick, & C.E. Borroni-Bird, "Vehicle of Change," *Sci. Amer.* **287**(4):67–73, Oct. 2002.
[97] "The Spirit of the Coming Age," in www.shell.com/home/media-en/downloads/scenarios.pdf.
[98] Thomas (ref. 53) points out that a \$0.01/gallon gasoline tax, ideally as part of a fuels feebate, would suffice to install hydrogen infrastructure in more 5% of the nation's major gasoline filling stations per year. Meanwhile, investments to sustain the gasoline infrastructure would fall by even more, and so therefore, presumably, would gasoline prices.
[99] See ref. 11.
[100] See ref. 89.
[101] Fifty MT H_2/y at LHV (120 MJ/kg) is 6 EJ/y. Used in quintupled-equivalent-efficiency vehicles, that would displace 30 EJ/y of gasoline-equivalent. World apparent consumption of gasoline in 2000 was 19.76 Mbbl/d or ~42 EJ (www.eia.doe.gov/emeu/iea/table35.html), and 30/42 is 0.71.
[102] See note 29.
[103] In 2000, all highway vehicles used 20.7 QBTU or 21.9 EJ of gasoline (77%) and diesel fuel (23%), 74% of it gasoline in light vehicles (ORNL *Transportation Energy Data Book*, www-cta.ornl.gov/cta/data/Index.html, edn. 22, p. 2-6). With 5η light vehicles and ≥2η medium-and-heavy vehicles, that 22 EJ of highway-vehicle petroleum fuel could be displaced by ~5.5 EJ of H_2, or ~6.5 times the estimated 0.84 EJ/y currently used by U.S. refineries (note 29). Displacing the gasoline alone would take ~4 times that refinery H_2 usage.
[104] The potential in class 3+ wind areas, net of environmental and land-use exclusions, is estimated at 1,210 TWh/y for North Dakota and 1,030 TWh/y for South Dakota (Pacific Northwest Laboratory, *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States*, 1991, not adjusted for the potential effects of recently discovered larger-than-expected high-level wind: C.L. Archer & M.Z. Jacobson, "Spatial and temporal distribution of U.S. winds and wind power at 80 m derived from measurements," *J. Geophys. Res.* **108**(D9):4289–4309 (2003)). At a nominal 75% electrolyzer efficiency, the total wind electricity from these two states could produce 50 MT/y of hydrogen, excluding electric and gas transmission losses and compressor energy. This illustrates the fallacy of claims that other than nuclear power, "there is no other place…to get the energy to make hydrogen in practical quantities": A.D. Robinson, ref. 37.
[105] A standard Linde natural-gas steam reformer releases 0.82 kg of CO_2 per standard m^3 of H_2 (Wurster & Zittel, *op. cit. supra*, ref. 45, Ch. 9), or 2.5 kgC/kg H_2. For illustration, Hypercar, Inc.'s *Revolution* concept SUV would use 0.64 kgH_2/100 km, so it would release 1.6 kgC/100 km if making its hydrogen from natural gas in this way, plus a small amount for the reformer's use and the retail compressor's net use of electricity. Its gasoline-engine equivalent (a Lexus *RX300*) is fivefold less efficient — 20 mi/gal or 0.12 kgC/mile or 7.4 kgC/100 km from the gasoline, plus roughly one-fourth for the related fuel cycle (ADL-DOE, *op. cit. supra*, ref. 51) — so, consistent with their efficiency ratio, it releases about five times more total carbon per mile than the *Revolution*.
[106] Based on note 88's *operating* costs alone, onsite electrolysis paying \$0.02/kWh can deliver hydrogen at the same cost as an onsite reformer paying \$5.67/GJ (HHV) for natural gas. Just the reported *operating* cost of *existing* U.S. nuclear plants (excluding major repairs, which are capitalized, and any increases beyond the currently socialized costs of waste disposal, security, third-party liability, etc.) averaged \$0.02053/kWh in 1996–2000 inclusive (mixed current \$), or \$0.0213/kWh (2000 \$), according to the consultant-edited data set presented by EIA, *Electric Power Annual 2000*, vol. 2, Table 13. Interestingly, the unedited data set for 1995–97 reported in *Nucleonics Week*, 18 June

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 average 1996 delivery cost for a U.S. kWh was ~\$0.025/kWh (as a small business, a filling station is a good surrogate for the average customer). The short-run marginal cost of *delivered* U.S. nuclear electricity is thus ~\$0.0463/kWh — competitive in hydrogen-producing operating cost with gas at \$16.8/GJ, equivalent to \$97/bbl oil. As stated earlier, only an extremely cheap source of delivered electricity can compete with onsite gas reformers as a source of hydrogen, and even existing nuclear plants, at operating cost only, clearly don't fit this description.

[107] Ref. 31 correctly notes that dedicated wind-to-hydrogen systems can considerably reduce the costs and losses of the wind turbines because they can provide variable-voltage DC rather than constant-frequency AC. To be sure, transporting energy from the Dakotas to Midwestern cities wouldn't be cheap; yet the U.S. Senate has little trouble voting as much as tens of billions of dollars in subsidies for a clearly uneconomic pipeline to transport 35 Tcf of stranded gas from Alaska's North Slope. (Such a pipeline, especially via the Canadian route, might make considerably more economic sense if it carried hydrogen instead, reformed at the wellhead with CO_2 reinjection.)

[108] Normally biomass is reformed by oxygen-blown partial oxidation, followed by CO shift and then purification of the hydrogen with standard amine scrubbing or pressure-swing adsorption. Air-blown gasification may suffice if the fuel cell will tolerate nitrogen impurity in the hydrogen. Reforming biomass may become cheaper with new non-platinum-group catalysts, *e.g*. G.W. Huber, J.W. Shabaker, & J.A. Dumesic, *Science* **300**:2075 (30 June 2003), www.sciencemag.org/cgi/reprint/300/5628/2075.

[109] A normal module uses 5.5 MW of electricity and produces 40 million m^3/y of hydrogen, but presumably it could also be smaller. A US\$43-million, 50-million-$m^3 H_2$/y Canadian plant announced in 1997 claimed 100% carbon utilization and zero pollution: Release, 15 Oct. 1997, "Kværner to build 'innovative' carbon black plant in Canada," www.kvaerner.com/group/.

[110] Opinions differ on whether windpower growth so far has merely "cherry-picked" unusual locations with surplus transmission already built and paid for, and hence whether the growth can continue as this resource is filled up. In some places, windpower may actually free up transmission capacity by supporting the grid at locations where power flow is in net deficit, avoiding the need to transmit power from central thermal generators farther away.

[111] Assuming equivalent marginal transmission investment requirements, if any, for both options.

[112] *New* nuclear plants, even without counting the marginal cost of electricity delivery, would incur a marginal cost many times (by most independent estimates, ~4–8 times) the old plants' short-run operating cost, or about ~\$0.08–0.15/kWh at the busbar, or about \$0.10–0.17/kWh delivered, conservatively assuming no need for grid expansion. This implies that new nuclear plants would need commercial retail gas prices on the order of \$36–62/GJ to compete in delivering electrolytic hydrogen. Those gas prices would be equivalent to oil prices around \$210–360/bbl, ~4–7× the highest world oil prices ever observed. Properly counting the capital costs of the reformer and electrolyzer would also make these nuclear results even more discouraging.

[113] A.B. Lovins *et al*., *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*, RMI, 2002, www.smallisprofitable.org.

[114] A typical General Atomics summary is at www.ch2bc.org/General%20Atomics/NuclearH2-27June02.pdf.

[115] It failed to do so in two of the years 1996–2000, and barely did in the other three (www.eia.doe.gov/cneaf/electricity/epav2/html_tables/epav2t13p1.html), despite using an incomplete definition of operating costs (particularly by excluding major repairs) and a favorably edited subset of actual costs (note 106).

[116] Experimental thermochemical water-splitting processes driven by nuclear heat, such as the predicted 40–45%-efficient 500°C copper-silver-chlorine process being explored by Argonne National Laboratory, might be cheaper than electrolysis, though most experts expect practical processes, such as the more usual sulfur-iodine cycle, would need at least 700˚C (DOE, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, 2003, Findings, p. 17, www.ne.doe.gov/geniv/Generation_IV_Roadmap_1-31-03.pdf#page=11). However, either way, this looks uncompetitive with natural-gas reforming by a factor of severalfold, so thermochemical water-cracking too is very unlikely to provide an economic rationale for building more nuclear plants. The current Senate energy bill nonetheless includes \$1 billion to build an experimental hydrogen-producing reactor at the Idaho National Engineering Laboratory. Nuclear fusion is even farther from reality and, like all fission fuel cycles, bears significant risks, including nuclear weapons proliferation, because its copious 14-MeV neutrons are effective for breeding fertile materials (^{238}U or ^{232}Th) into high-grade bomb materials (^{239}Pu or ^{233}U, respectively).

[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 OECD vehicle fleet increases OECD gas demand by ≤5%.
[129] Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies, *Scenarios for a Clean Energy Future*, ORNL/CON-476 and LBNL-44029, 2000, www.ornl.gov/ORNL/Energy_Eff/CEF.htm, readily identified cost-effective opportunities to save 17% of U.S. 2000 natural-gas consumption by 2020 from a base case that already included significant efficiency gains.
[130] J.B. McCormick, personal communications, 2002.
[131] R.W. Jewell, "Natural Gas — What Is Going On?!," 18 March 2003, Dow Chemical Company, notes that shaving 5% off the peak U.S. electric load would cut U.S. natural-gas consumption by 1.5 Tcf/y, or one-fifth of power-sector gas consumption; by 10%, 2.3 Tcf/y, or a tenth of the total gas market. This calculation appears to be conservative because it apparently uses average heat rates, whereas the peaking plants that are run least have the worst heat rates (although the fewer hours they run, the less gas they use). RMI is undertaking a more precise calculation.
[132] Until the U.S. ratifies the Kyoto Protocol, which is expected to enter in force as soon as Russia ratifies it, U.S. industries will be at a competitive disadvantage because they cannot trade carbon reductions as their foreign competitors can. Some private traders are already making private carbon markets in the U.S., but Federal opposition to having any official rules is making the market thinner and less lucrative than it would otherwise be.
[133] See ref. 53.
[134] See the Princeton University/BP/Ford Carbon Mitigation Initiative's work at www.princeton.edu/~cmi/.
[135] I.M. Held & B.J. Soden, "Water Vapor Feedback and Global Warming," *Ann. Rev. En. Envt.* **25**:441–475 (2000).
[136] European studies have shown the value of flying cryoplanes below the tropopause — typically below 28,000 ft (9 km) in summer and 21,000 ft (7 km) in winter — adding only modestly to flight time (because less ascent/descent is required) and ~1–4% to operating cost: W. Zittel & M. Altmann, "Molecular Hydrogen And Water Vapour Emissions In A Global Hydrogen Energy Economy," *Procs. 11th World Hydr. En. Conf.* (Stuttgart, 1996), www.hydrogen.org/knowledge/vapor.html. M. Gauss *et al.*, "Impact of H_2O emissions from cryoplanes and kerosene aircraft on the atmosphere," *J. Geophys. Res.* **108**(D10):4304 (21 May 2003), www.agu.org/pubs/crossref/2003/2002JD002623.shtml, found that 1 km increase in cruising altitude could double cumulative water vapor additions to the extremely dry air in the stratosphere. They analyzed completely replacing

the NASA-projected 2015 inventory of subsonic kerosene aircraft with subsonic liquid-hydrogen-powered cryoplanes, which emit 2.55 times as much water vapor per unit of fuel energy (but with important physical differences in contrail formation — D.S. Lee *et al*., "Uncertainties in radiative forcing of climate from aviation contrails and aviation-induced cirrus," DERA/AS/PTD/CERA000103, Defence Evaluation and Research Agency (UK), 2000, and L. Ström & K. Gierens, *J. Geophys. Res.* **107**(D18):4346 (2002) — and possibly different short- from long-term effects — www.op.dlr.de/~pa3u/ast2001.html). Some 2002 calculations cited by Gauss *et al*. even suggest that cryoplanes could have less contrail impact than kerosene aircraft, so water-vapor impact would dominate. Assuming an all-subsonic-cryoplane fleet so large that it burns twice the current world production of hydrogen, Gauss *et al*. found an increase in radiative forcing at the tropopause by a global average of zero to fivefold depending on season (0.0027–0.0135, averaging 0.0026, W/m^2). That average is about 15 times smaller than the avoided CO_2 effect of the same cryoplanes (assuming climate-safe hydrogen), and is about 5% of the 0.05 W/m^2 1992 radiative forcing by global subsonic aviation found by the Intergovernmental Panel on Climate Change's 1999 study *Aviation and the Global Atmosphere* (www.grida.no/climate/ipcc/aviation/index.htm), which in turn was about 3.5% of the total radiative forcing caused by human activities. The IPCC's 1999 (pre-slump) forecasts predicted total radiative forcing of about ~0.1–0.2 W/m^2 in 2020 and 0.13–0.56 W/m^2 in 2050. Thus subsonic cryoplanes would be very beneficial if they reduced this to only ~0.0026 W/m^2. Gauss *et al*. caution, however, that *super*sonic cryoplanes could cause a radiative forcing of nearly 0.05 W/m^2, comparable to the current subsonic kerosene fleet, and that even with a subsonic fleet, stratospheric and polar flight is to be discouraged.

[137] At www.eere.energy.gov/hydrogenandfuelcells/codes/faqs.html#needs.

[138] As an upper bound using extreme assumptions: if all the world's half-billion light vehicles were 5η vehicles as big and capable as the *Revolution* concept SUV, each driven the U.S. average of about 11,000 miles per year, they'd emit half a billion metric tons of water per year. If this water were all "new" (none from electrolysis or steam reforming), it would add 0.004% per year to the atmospheric water inventory. For comparison, the carbon dioxide concentration in the atmosphere rose in the 1990s by half a percent per year, or two orders of magnitude more.

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

[140] J. Bell, in Sierra Club Energy Forum, www.sierraclub.org/powerlunch/topic13.asp, with reply from Ned Ford, and "Is Hydrogen Risky Business?," *E Magazine*, May/June 2003, p. 8, with reply from D.J. Friedman, www.emagazine.com/may-june_2003/0503advdis.html; also posted under "Using Hydrogen Gas to Store Intermittent Renewable Energy" at www.jimbell.com/theway.html#hydrogen, 3 September 2002. Mr. Bell has since withdrawn his concerns on this issue, subject to any future discoveries (pers. comm., 28 May 2003).

[141] Only tiny traces of molecular hydrogen (~0.51 ppm or ~180–200 MT H_2) are found in the Earth's atmosphere, often due to reactions related to automobile pollution: D.H. Barnes *et al*., "Hydrogen in the atmosphere: Observations above a forest canopy in a polluted environment," *J. Geophys. Res.* **108** (D6):4197 (2003), www.agu.org/pubs/crossref/2003/2001JD001199.shtml, and for a broader survey, Zittel & Altmann, *op. cit. supra*, ref. 136.

[142] Total methane emissions from *all* fossil-fuel activities are estimated by the 2001 Intergovernmental Panel on Climate Change to be ~89–110 million T/y, equivalent to 6% of 2000 natural-gas production of 2.4 trillion m^3 or 1.6 billion T, but most of that is gas leaking from coal beds; only about 1% of natural-gas throughput leaks from natural-gas wells, compressors, pipelines, retail distribution systems, and other facilities. Older figures for the former Soviet bloc cited gas losses around 7–20%, but most of that was theft, and the much smaller fraction that was actual leaks has been or is being fixed; *e.g.*, total losses from a West Siberian field to Central Europe, over 6,000 km away, were measured at ~1% in 1996–97 (*Annex "Full Background Report" to the GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems — A European Study*, L-B-Systemtechnik GmbH (Ottobrunn, Germany), www.lbst.de/gm-wtw, pp. 74–75). Total U.S. natural gas "leaks and flares," nearly all of it actually flares rather than leaks, totaled 1.1% of 1996 production and falling; the worldwide total is probably scarcely higher, and in industrial countries, it's probably down to only ~0.1–0.5%, with 0.05% possible in new distribution systems (M. van Walwijk, M. Bückmann, W.P. Troelstra, & P.A.J. Achten, *Automotive Fuels Survey: Part 2. Distribution and Use*, Dec. 1976, p. 176, International Energy Agency (IEA/AFIS), Paris, www.iea.org/tech/infocentres/AFIS.htm). A 0.05% leakage rate is reported by the Italian pipeline system of SNAM Rete Gas, and 0.2% by the whole system of Gas Natural España. See M.Q. Wang & H.-S. Huang, *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas*, ANL/ESD-40, 1999, Argonne National Laboratory, www.transportation.anl.gov/pdfs/TA/13.pdf, at p. 36; M.Q. Wang, *GREET 1.5 — Transportation Fuel-Cycle Model*, Vol. 1, pp. 57–59, ANL/ESD-39, Vol. 1, August 1999, http://www.ipd.anl. gov/anlpubs/1999/10/34035.pdf; and further GRI/EPA, EIA, Canadian, GM, and IEA data kindly provided by Dr. Wang

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.

[144] *Id.*

[145] See http://smallcomets.physics.uiowa.edu/.

[146] The small comets add on the order of a million metric tons of water per day (*id.*). In contrast, rather high (1%) leakage and 100% atmospheric escape (*vs.* ~0.04% actual) from a hydrogen economy relying solely on splitting surface water, and providing the same amount of delivered energy as today's global energy system does (hence delivering a lot more services than today's ~420 EJ/y does, since hydrogen's end-use is more efficient than that of fossil fuels), would lose ~90 kT/d of hydrogen, equivalent to about 0.8 MT/d of water — near the low end of the range for small-comet additions.

[147] T.K. Tromp, R.-L. Shia, M. Allen, J.M. Eiler, & Y.L. Yung, "Potential Environmental Impact of a Hydrogen Economy on the Stratosphere," *Science* **300**:1740–1742 (13 June 2003).

[148] Zittel & Altmann, ref. 136.

[149] S.A. Sherif, N. Zeytinoglu, & T.N. Veziroglu, "Liquid hydrogen: potential, problems, and a proposed research program," *Intl. J. Hydr. En.* **22**, 683 (1997).

[150] Québec-to-Hamburg liquid-hydrogen barges could have zero boiloff if properly insulated: W. Zittel, Ludwig-Bölkow-Systemtechnik GmbH, zittel@lbst.de, personal communications, 16 and 17 June 2003, www.l-b-systemtechnik.com/e/Projekte/Euro_Quebec_Phase_II_89-90.htm (summary), and J. Gretz, B. Drolet, D. Kluyskens, F. Sandmann, & O. Ullmann, "Phase II and Phase III,0 of the 100 MW Euro-Quebec Hydro-Hydrogen Pilot Project EQHHPP, *Procs, 9th World Hydr. En. Conf.*, Paris, 22–25 June 1992, pp. 1821–1828.

[151] The fuel tanks of cryoplanes, unlike those of space rockets, would be kept cold continuously by refueling at each stop; would be depleted soon after each refueling; would use their boiloff for fuel; and would spend most of their time in the cold of the upper atmosphere rather than sitting at ground level. Major airports would use very large (hence low-boiloff) tanks fed by cryogenic pipelines, not by small truck- or railborne tanks, and could use boiloff to fuel stationary generators. A full 2015 global fleet of cryoplanes would use ~96 MT/y of LH_2 (S. Marquart, R. Sausen, M. Ponater, & V. Grewe, "Estimate of the Climate Impact of Cryoplanes," *Aerosp. Sci. Technol.* **5**, 73–84 (2001)) — 10^{-1} of total H_2 usage in a global all-H_2 economy using no renewable energy directly. Actual cryoplane H_2 consumption should also be reduced by the greater efficiency of cryoplanes (see ref. 50).

[152] *E.g.*, the current German industrial hydrogen system's 0.1% leak rate plus a bit more for retail distribution and some special but minor losses associated with fueling and operating fuel-cell vehicles. Prospective leak rates for entire hydrogen systems are being carefully assessed by Dr. Mark A. Delucchi at the University of California/Davis.

[153] A.B. Lovins, letter submitted 17 June 2003 to *Science*, to be posted at www.rmi.org. Other authors have also pointed out additional problems with the CalTech authors' analysis.

[154] The 2001 U.S. average commercial-sector electricity tariff of $0.0791/kWh is equivalent in heat content to crude oil at ~$134/bbl or to gasoline at $2.90/USgal (HHV), not counting relative end-use efficiencies.

[155] See ref. 22.

[156] This concept car was shown at the 2003 North American Auto Show in Detroit. Its mass, acceleration, drag, and cargo volume were not revealed. Based on the *Focus* small-SUV platform, it uses unusual materials, modularity, and other features officially summarized at www.ford.com/en/vehicles/autoShows/detroit2003/ford/modelU/default.htm. Its H_2-optimized 2.3-L 4-cylinder engine, despite supercharging and two-stage intercooling, becomes about one-fourth more efficient but is derated 22%, requiring 3.6 kWh of storage and a 35-kW torque-boosting electric motor. For a 300-mile range, the 7 kg of 700-bar H_2 is stored in four tanks under a subfloor, making the vehicle quite high. Fuel economy is equivalent to 45 mpg (5.2 L/100 km), less than half that of the larger *Revolution* fuel-cell concept car but 69% better than the equivalent automatic-transmission 2003 *Focus* base model at 26.7 mpg (8.8 L/100 km).

[157] This assumes that the car is fueled only with hydrogen rather than with both hydrogen and gasoline, for three reasons: the nuisance of having to insert two fuels, the difficulty of optimizing one engine for two such different fuels (requiring, for example, different injectors), and gasoline's compromises in efficiency and emissions.

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

[159] C.E. Thomas, "Hydrogen-Fueled Vehicles: Hybrids vs. Fuel Cells," Intl. Veh. Technol. Sympos on Clim. Change, Calif. Air Resources Board (Sacramento), 11–13 March 2003, www.h2gen.com/PDF_Documents/GHG-HEV_vs_FCV_Rev_B.pdf.

[160] *Id.*

[161] *Id.*

[162] T.E. Lipman, "Integration of Motor Vehicle and Distributed Energy Systems," *Encyc. of Energy*, in press, Academic Press, 2004; see also www.udel.edu/V2G/, www.acpropulsion.com/, and http://socrates.berkeley.edu/~rael/fuelcell.html.
[163] For example, Hypercar, Inc.'s 5-seat *Revolution* concept car has the same curb mass and drag coefficient as the *Insight* — albeit higher frontal area — mainly because carbon fiber is so much lighter than even aluminum.
[164] A.B. Lovins *et al.*, *Out of the Oil Box: A Roadmap for U.S. Mobilization*, RMI, in preparation, 2003.