10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, Virginia, 7–9 April 1999

A Strategy for the Hydrogen Transition

Amory B. Lovins, Director of Research, and Brett D. Williams, Senior Research Associate
Rocky Mountain Institute

Abstract

A rapid, practical, and profitable commercialization path for fuel cells and H_2 can be executed by coordinating convergent trends in several industries. This strategy relies on existing technologies, can begin immediately, and proceeds in a logical and viable sequence. It has two preconditions: uncompromised ultralight-hybrid vehicles whose inherently high efficiency permits their fuel-cell stacks to rely on conveniently compact onboard tanks of compressed gaseous H_2, making onboard liquid-fuel reformers unnecessary and uncompetitive; and integration of fuel-cell market development between vehicles and buildings.

As a first step, fuel-cell co- or trigeneration could currently compete in many buildings by virtue of its thermal credit. It could yield even greater economic value wherever electric distribution grids are old or congested, or where other "distributed benefits" are important and rewarded. Its H_2 could be made in the building by a mass-produced "hydrogen appliance"—either an offpeak electrolyzer or a natural-gas steam reformer.

Next, the huge fuel-cell market in buildings (which use two-thirds of all U.S. electricity), supplemented by industrial niche markets, would soon cut fuel-cell costs to levels competitive in vehicles. Low-tractive-load Hypercars™ could adopt fuel cells at severalfold higher prices, hence several years earlier, than conventional cars. The general-vehicle market could then be opened to hydrogen by first using the spare offpeak capacity of buildings' H_2 sources to serve vehicles too—particularly vehicles whose drivers work or live in or near the same buildings. Further, those vehicles' daytime use as plug-in ~20+-kW_e power plants could repay a significant fraction of their lease cost. This building/vehicle integration could make gaseous-H_2 fueling practical without first building a new upstream bulk-supply and distribution infrastructure. It would work better and cost less than onboard liquid-hydrocarbon reforming. Ultimately it could provide more than 3 TW_e of U.S. generating capacity, enough in principle to displace virtually all central thermal power stations.

As both stationary and mobile applications for fuel cells built volume and cut cost for dispersed but stationary reformer and electrolyzer appliances, those H_2 sources would also start to be installed freestanding outside buildings. Before long, the growing H_2 market would then justify further competition from upstream bulk supply, especially from climatically benign sources. Such options include converting hydroelectric dams (or other renewables) to "Hydro-Gen" plants that earn far higher profit by shipping each electron with a proton attached, and R.H. Williams's concept of wellhead reforming of natural gas with CO_2 reinjection. The latter option's three possible profit streams—high-value hydrogen-fuel sales, enhanced hydrocarbon recovery, and potential carbon-sequestration credits—are already attracting large energy companies. Its ~200-year climate-safe CH_4 reserves (at roughly current rates of consumption) could also provide a long bridge to a fully renewable energy system. The diverse and dynamic portfolio of hydrogen sources—up- and downstream; renewable and nonrenewable; based on electrolysis, reforming, or other methods; and with small to no net climatic effect—would ensure healthy price competition and robust policy choices.

Introduction

Transitional paths to fuel cell-powered road vehicles and to a wider hydrogen economy are conventionally assumed to be slow, costly, and difficult, due to two main obstacles:

- A large new infrastructure for producing and distributing bulk hydrogen, costing tens or hundreds of billions of dollars for the United States alone, is normally assumed to be required before hydrogen use can become widespread.[1]
- Technological breakthroughs in hydrogen storage are also presumed to be needed because the tankage required for onboard storage of compressed hydrogen gas is currently too bulky to fit acceptably into light and medium vehicles, while cryogenic storage is considered costly and complex.

These twin barriers are commonly assumed to require that fuel-cell vehicles, whether transitionally or permanently, carry onboard fuel processors[2] fueled by gasoline, methanol[3], or other liquid hydrocarbons. However, that approach faces formidable technical and economic challenges: Barring a breakthrough, fuel-cell systems based on onboard gasoline reformers offer little or no advantage over advanced gasoline-fueled internal-combustion-engine propulsion.[4] The case for methanol reforming, although perhaps better, still suffers from modest and compromised net benefits. Onboard reforming would entail slow, uncertain, and niche-focused adoption of fuel-cell vehicles, especially if a new infrastructure were required for safe handling of methanol or if reformers required newly optimized, high-purity forms of gasoline or other reformer feedstocks.

These discouraging conclusions, however, are artifacts of two initial assumptions:

- that the vehicles must be inefficient—essentially conventional vehicles converted from gasoline-fired Otto engines to liquid-reformer-fueled fuel cells—and
- that the deployment of fuel cells in stationary and in mobile applications can be considered independently.

Neither of those widespread assumptions adequately reflects today's technological and market opportunities. This conceptual paper—emphasizing and somewhat simplifying the basic logic—synthesizes an argument that changing both assumptions can yield an effective transitional strategy to the widespread use of hydrogen. The strategy proposed here is not the only one that could work, but it does appear to offer significant attractions.

Specifically, starting with very efficient vehicles, and properly integrating the deployment of fuel cells in vehicles and in buildings, can yield a transition to hydrogen that is rapid, relies on established technologies, avoids most of the normally presumed difficulties, and should prove profitable at each step. As should become clear in the marketplace over the next year or two, this alternative strategy is already starting to be accepted by some large energy and car firms. For the reasons described below, we expect its logic will gradually make it the dominant paradigm of the emerging hydrogen industry.

Superefficient light vehicles

Impressive progress in the 1990s in the operational and cost parameters of fuel cells—mainly but not exclusively the proton-exchange-membrane (PEM) designs assumed in this discussion[5]—have diverted attention from an equally important revolution in automotive design. In pursuit of superior, uncompromised, and extremely fuel-efficient vehicles, offering important advantages for both drivers and manufacturers, a new design approach is emerging that would also make the vehicle platform ready for fuel cells and for their direct fueling with compressed hydrogen gas.

Since 1991, a coherent and attractive automotive concept has been suggested and refined that could make any type of light road vehicle (plus many heavy ones such as buses and trucks) severalfold lighter-weight and lower-drag than conventional versions. This requires a highly integrated ultralight design, typically using a body molded from advanced polymer composites, plus close attention to design synergies, mechanical simplification, and open-architecture whole-platform software and electronics.[6] These features could together cause mass, cost, and complexity to decompound markedly, and could reduce curb mass by about 2–3-fold, aerodynamic drag by 2-fold, and rolling resistance by 2.5–5-fold. These reductions could in turn cut tractive loads by about 2–3-fold and increase overall vehicle efficiency (fuel to traction) by 4–8-fold[7], so that:

- severalfold less fuel-cell capacity is required: ~25–30 kW_e for a 4-passenger sedan or ~30–50 kW for a 5–6-passenger sedan or larger light-duty vehicle[8];
- this reduced capacity makes a fuel-cell price on the order of $100/$kW_e$ competitive—a severalfold higher price than could compete in a less efficient conventional car;
- on normal experience-curve assumptions, that higher tolerable price is likely to be achieved a few years (doublings of cumulative production) earlier than the severalfold lower price normally posited[9];
- the lower required fuel-cell capacity also increases the range of tolerable fuel-cell mass and volume per kW;
- direct-hydrogen fueling yields reasonable driving ranges with a compressed-gaseous-hydrogen tank combining reasonable cost, packagable bulk, and very low mass[10];
- the direct-hydrogen fueling maximizes the fuel cell's capacity and efficiency, reinforcing its advantage in mass, volume, range, and cost; and
- the combination of the more efficient platform with more efficient conversion of fuel energy into traction[11] permits the use even of costly sources of hydrogen fuel without raising fuel-cost-per-km to uncompetitive levels.

These attributes are achievable without compromising any others desired by car owners or manufacturers: on the contrary, design synergies can make such a vehicle equal or superior in all respects to current market offerings. Manufacturers also gain key competitive advantages, including up to an order of magnitude decrease in product cycle time, investment requirements, body parts count, and assembly effort and space. By the end of 1998, such advantages for both customers and manufacturers had led billions of dollars[12] to be committed to this line of development, with a doubling time below two years, in extensive proprietary efforts by both established and intending automakers. Many key elements of this design approach (called here by Rocky Mountain Institute's trademarked term “Hypercar™”) have already appeared in concept cars and market platforms in the late 1990s.[13] Widespread market introduction and rapid spread of a wide range of vehicles incorporating the essential elements of that ultralight-hybrid design synthesis, including fuel-cell versions, appear inevitable soon after the turn of the century.

Of course, a Hypercar could make its traction power onboard from any liquid fuel, including gasoline, methanol, or biofuels, using an engine- or turbine-driven generator. It would simply not be as clean or efficient as a direct-hydrogen fuel-cell version. In round numbers, an engine-driven, liquid-fueled Hypercar would normally achieve about 2–3 L/100 km, while a hydrogen-fuel-cell version would achieve roughly 2 or fewer L/100 km (both expressed as liters of gasoline-equivalent). Since the Hypercar relaxes the fuel-cell-cost and tank-packaging constraints that make direct hydrogen fueling unattractive in conventional fuel-cell-powered cars[14], it also makes unnecessary the many penalties in cost, mass, volume, efficiency, and other attributes that have been well established as consequences of the onboard liquid-fuel reforming strategy.[15]

Thus the market-driven adoption of a superefficient car relieves the vehicle design constraints that are normally presumed to require onboard reformers and liquid fuels, and unlocks the many benefits of compressed hydrogen gas fueling. The major constraints remaining are the cost of the fuel cell and the buildup of hydrogen refueling infrastructure. Relieving these constraints requires careful coordination between deployment in both vehicles and buildings.

Deployment of fuel cells in buildings and vehicles

To be competitively used in light-duty vehicles, even in Hypercars, fuel cells must become dramatically less expensive than they are in early 1999 at the dawn of their commercial mass-production. There is little doubt that this will occur if they are engineered for and put into mass-production. Compared to car engines, with their thousand parts made chiefly of heat-treated metal alloys and subject to the stresses of motion and explosion, fuel cells should ultimately prove cheap, rugged, and easy to make. It is a truism of modern manufacturing, verified across a wide range of products, that every doubling of cumulative production volume typically makes manufactured goods about 10–30 percent cheaper. There is every reason to believe fuel cells will behave in the same way. In 1998, handcrafted fuel-cell stack prototypes sold for thousands of dollars per kilowatt. In early mass-production, a kilowatt will probably fall to $500–$800, and, as production expands over the following few years, to around $100. That’s only severalfold more than the cost of today’s gasoline engine/generators (after more than a century of refinement), about tenfold cheaper than a coal-fired power station, and severalfold cheaper than just the *wires* to deliver that station’s power to a building, where the fuel cell could already be.

When fuel cells are manufactured in very large volumes, using such innovative designs as (for example) molded roll-to-roll polymer parts glued together, they could become extremely cheap—probably less than $50 per kilowatt[16], which is about a fifth to a tenth the cost of today’s cheapest combined-cycle gas-fired power stations. Most automakers assume they need such low costs before fuel cells can compete with internal-combustion engines. As described earlier, however, Hypercars need severalfold fewer kilowatts to provide excellent performance, so they can tolerate higher costs, perhaps as high as about $100 per kilowatt. This, and their correspondingly higher tolerance of immature specific mass and volumetric power ratings, gives Hypercars a few years' head start in adopting fuel cells—an important market advantage for both Hypercars and fuel cells.

However, exclusive focus on cars leads to the incorrect conclusion that fuel-cell costs must be driven down to automotively acceptable levels by brute-force, loss-leader scaleup of production for cars. It is more plausible that the initial markets that build production volume and cut cost will instead come from buildings.[17] Enough production volume to achieve $100 per kilowatt could readily come from using fuel cells first in buildings—a vast potential market, since buildings use two-thirds of America's total electricity. For these reasons, several large makers of cars and car parts are crossing traditional boundaries and quietly launching significant ventures to commercialize fuel cells in stationary as well as mobile applications.

The main reason to start with buildings is that fuel cells can turn 50 or more percent of the hydrogen's energy[18] into highly reliable, premium-quality electricity, and the reminder into 70°C pure water—ideal for heating, cooling, and dehumidifying buildings using a modular "balance-of-system" black box which several capable firms are already developing.[19] In a typical building, such services would help pay for natural gas and a fuel processor.[20] With the fuel expenses thus largely covered, electricity from early-production fuel cells should be cheap enough[21] to undercut even the operating cost of existing coal and nuclear power stations, let alone the extra cost to *deliver* their power, which in 1996 averaged 2.4 cents per kilowatt-hour.[22] Announced market entrants for packaged, natural-gas-reformer-fueled fuel-cell cogeneration systems include General Electric, which says it plans to market the household-scale Plug Power system late in the year 2000.

Even the handmade-by-PhDs fuel cells of 1998 could have turned a profit in buildings if deployed initially to buildings in those neighborhoods where the electrical distribution grid is fully loaded and needs costly expansions to meet growing demand, or where it is nearing the end of its service life and needs life-extension or replacement.[23] Over 100 North American utilities are already prospecting for such "hot spots" where local generation or load reduction can be targeted by "Local Integrated Resource Planning" specifically to avoid or defer costly distribution investments.[24] In addition to avoiding distribution costs and losses, fuel cells can offer the utility such valuable "distributed benefits" as reactive power support, stability support (via very fast ramp rates), improved distribution circuit management, simplified fault management, and reduced reserve margin and spinning reserve. Moreover, customers benefit from enhanced reliability and unsurpassed power quality, which can displace uninterruptible power supplies for computers and other critical applications, while investors realize important reductions in financial risk. Collectively, such distributed benefits can often increase the economic value of decentralized generators by about an order of magnitude.[25] Counting these benefits is not necessary to make $500/kW_e$ fuel cells competitive in many buildings, but it certainly enhances their margin of advantage and hence accelerates their market adoption. Nor is it necessary to perform detailed and sophisticated analyses to conclude that the site-specific attractiveness of such a cheap, efficient power and heat source should be quite robust in a wide range of settings.

Besides co- or trigeneration (electricity plus heating plus cooling) in buildings, fuel cells offer a nearly ideal fit to some important industrial niche markets. For example, hundreds of microchip fabrication plants, plus another $169 billion worth on the drawing-boards as of 1997, each use an average on the order of 15 MW_e with a capacity factor over 90%. Such a "fab" typically loses about 6–8% of its $5–10-million annual electric bill to the standby losses of a giant and very costly uninterruptible power supply required by its ultraprecise processes. That UPS can be eliminated by a suitably configured array of fuel cells and inverters designed for the desired level of reliability. Moreover, the fuel cells' ~70°C waste heat is well matched to the fab's requirements for process heating and cooling; the clean hot water created by the fuel cells is an ideal feedstock for the fab's ultrapure water system; and the manufacturing process requires pure hydrogen as a reagent, offering the opportunity to share the hydrogen source. These features appear to make even early production PEM fuel cells (or competing types such as the ONSI phosphoric-acid stacks) strong candidates for immediate retrofits into many existing fabs, and the power supply of choice for all new ones. Nor is chipmaking the only important industrial niche application.

Early adopters of fuel cells will naturally prefer those applications and locations that offer the most favorable combination of fuel cost, electricity and thermal value, temporal patterns and matching of electric and thermal loads (both as influenced by load management, storage, and especially end-use efficiency), distributed benefits, net-metering laws, interface requirements, pollution credits, and other technical, economic, and institutional conditions. Although site-specific analysis will be initially important, even a modest subset of the in-building generation market can yield an aggregate fuel-cell capacity larger than should be required to achieve a cumulative production volume consistent with the ≤\$100/kW_e system costs needed for deployment in Hypercars.

However, once fuel cells become cost-effective for, and are installed in, a Hypercar, it becomes more than just a car. It is also, in effect, a clean, silent, ultrareliable power station on wheels, with a generating capacity of at least 20 kilowatts. The average American car is parked about 96 percent of the time, usually in habitual places. Suppose you pay an annual lease fee of about \$4,000–5,000 for the privilege of driving your "power plant" the other 4 percent of the time. For much of the rest of the time, rather than plugging your parked car into the electric grid to recharge it—as battery cars require—you plug it in[26] as a generating asset. While you sit at your desk, your power-plant-on-wheels is sending 20+ kilowatts of premium-quality electricity back to the grid.[27] You're automatically credited for this production at the real-time price, which is highest in the daytime: you're probably running the power plant at the place and time at which its output is most valuable. Thus your second-largest, but previously idle, household asset is now repaying a significant fraction of its own lease fee.[28]

If a modest fraction of drivers took advantage of this deal on a consistent basis, most or all existing coal and nuclear power plants could in principle be displaced, because ultimately the U.S. Hypercar fleet could have four or more times the generating capacity of the national grid.[29] Fuel cells will not be the only formidable competitor to central thermal power stations, but they may well be the most ubiquitous. As Asea Brown Boveri's Bertrand Dusseiller correctly notes, the rated prime-mover power of the automobiles now manufactured *each year* exceeds the total rated capacity of the world's power stations. Even though the latter have far longer operating lives, and Hypercars would have prime movers severalfold smaller than today's car engines, reducing the duplication between power stations and mobile generators by more fully using automotive generating capacity is clearly an important opportunity—especially since cars, unlike central power stations, tend to be located very near the electrical loads resulting from human activity.

Fueling the hydrogen transition: start decentralized

Perhaps surprisingly, the key to this revolution is not so much the fuel cell—many capable firms are working overtime to start mass-producing them early—but rather how fuel cells' best source of energy, hydrogen gas, will be manufactured, delivered, and stored. Two hurdles on the way to the hydrogen economy are commonly presumed: safety and the evolution of infrastructure for hydrogen fueling.

For fuel-cell cars, the often-expressed concerns about hydrogen safety are misplaced. Although discussion of hydrogen safety often evokes images of the 1937 *Hindenburg* disaster, former NASA scientist Addison Bain recently found that the airship's envelope, which was a cotton substrate coated with an aluminized cellulose acetate butyrate dopant—a cousin to rocket fuel—was very susceptible to the electrically-charged atmospheric conditions at Lakehurst at the time of the incident and was the probable cause of the fire.[30] The hydrogen, the protective lacquer on the aluminum airframe, and onboard diesel-oil did of course catch fire, but the envelope probably would have ignited without the hydrogen. Further, the hydrogen apparently did not explode and its unique burning properties kept the bulk of the fire in a cloud swirling above the passenger compartment. Sixty-two of the passengers and crew were able to ride the airship to the ground and survive, while 35 on board were killed from burns—but probably not directly by the hydrogen fire.

Although no fuel is free from potential hazard, carrying a tank of compressed hydrogen in an efficient car could actually be safer than carrying an equivalent-range tank of gasoline.[31] The car's inventory of hydrogen would be modest[32] and would typically be stored in an extremely strong carbon-fiber tank. Unlike spilled gasoline, escaped hydrogen likes nothing better than to dissipate—it's very buoyant and diffuses rapidly. It does ignite easily, but this requires a fourfold richer mixture in air than gasoline fumes do, or an 18-fold richer mixture (plus an unusual geometry) to detonate. Moreover, although its flame is invisible, a hydrogen fire can't burn you unless you're practically inside it, in contrast to burning gasoline and other hydro*carbons* whose white-hot soot particles emit searing heat that can cause critical burns at a distance.

Hydrogen, then, would make an excellent fuel. Fortunately, it's not necessary, as is often assumed, to delay the deployment of fuel cells in vehicles and buildings for decades while first building a vast new infrastructure to deliver hydrogen. Nor do automakers need to go through an awkward and costly transitional phase of fitting a fuel processor—a sophisticated portable thermochemical plant—into the car so it can convert liquid fuels (gasoline or methanol) into hydrogen onboard.[33] Instead, a new hydrogen infrastructure could be built step by step, using established methods and markets that could each be profitable. How can this transition actually occur?

Hydrogen technology isn't new. Producing hydrogen is a little-known but large and mature industry.[34] Making hydrogen now consumes about one percent of total U.S. primary energy and five percent of natural gas. Essentially all the hydrogen is now used as an onsite reagent, mainly for refining petroleum and for manufacturing petrochemicals, food, and electronics. Industry now either uses grid electricity to split water in an electrolyzer, or more commonly, reforms natural gas. However, reforming or electrolyzing need not be done industrially, at the scale of a refinery; it can also be efficiently and cost-effectively carried out at the scale of an apartment building, an office or retail building, or a neighborhood. One water-heater-sized, mass-produced "fuel appliance" can produce enough hydrogen to serve the fuel cells in one big building or dozens of cars.[35]

The strategic advantage of initially using "the existing natural gas pipeline system or the ubiquitous electrical power grid as the backbone of the hydrogen infrastructure system" is that "Hydrogen is produced where and when it is needed, in quantities that match the incremental growth of [fuel-cell] sales, minimizing the need for multi-billion-dollar investments prior to the introduction of sufficient numbers of [fuel cells] to provide adequate return on investment."[36] In addition, thanks to economies of production scale for the hydrogen appliances, the hydrogen costs less than centrally produced hydrogen requiring new pipelines or other distribution means[37]; but upstream bulk supply (discussed below) can still be added later as it becomes justified. Further, as other, more renewable, ways of producing hydrogen become available and economic, they too can be adopted without waiting for the vehicle fleet's technology to turn over yet again, as would be required by liquid-reforming scenarios. This innovation- and evolution-friendliness is an important strategic advantage.

What's missing is the step that bridges from initial, cost-cutting deployment of fuel cells in buildings to fuel cells' later rapid deployment in hydrogen-fueled cars. This bridge can be built by noting that the hydrogen appliances initially installed to serve fuel cells in buildings (in combination with the hydrogen appliances built to fuel public and private vehicle fleets) represent a constellation of hydrogen sources available also to cars. In particular, suppose fuel-cell Hypercars are leased first to the people who work in areas with buildings where fuel cells have already been installed. (The same utility could even lease both.) As you park your fuel-cell Hypercar at work[38], you plug into both the electricity grid and a snap-on fuel line bringing surplus hydrogen from the fuel appliance in the building. Since that device isn't normally kept fully occupied, in its spare time it makes a surplus of hydrogen, reducing the need to build a whole new infrastructure of hydrogen sources dedicated solely to cars.[39] This approach makes the profits of cars-as-plug-in-power-plants promptly available to a set of drivers far larger than those who operate centrally fueled vehicle fleets. In addition, the high purity of the hydrogen required for long life, low catalyst loading (hence low cost), and high efficiency in the buildings' fuel cells also supports the same qualities in the mobile fuel cells fueled by the same hydrogen appliances.

The next stage of expansion for hydrogen supply follows naturally from the in-building initial phase. The more owners of general-market vehicles acquire hydrogen-fueled Hypercars or other vehicles, the more entrepreneurs will want to start installing street-corner "gas stations"[40] based on the same inexpensive hydrogen production appliances, using either natural gas or electricity, that will already be mass-produced to supply the fuel cells inside buildings.[41] At the January 1999 Detroit Auto Show, Ford cited studies showing that hydrogen "can be cost-competitive with [U.S. taxed] gasoline on a cost-per-mile-driven basis if generated by [such] small factory-built [fuel]...appliances capable of supporting up to 100 vehicles." The retail margin available is far higher than already motivates the widespread establishment of gasoline filling stations, which suffer from cutthroat commodity competition, refiner and wholesale dominance, and high capital cost (including new precautions against leaking underground tanks). Initially, these distributed hydrogen sources will tend to cluster in nodes, corridors, and such regions as Southern California where air quality or other circumstances encourage early adoption. Gradually, economies of scale in hydrogen supply and utilization will fill the geographical thin spots.[42]

This approach offers several strategic advantages. It uses idle offpeak capacity in the natural-gas and electricity distribution systems that have already been installed and paid for. It is build-as-you-need and pay-as-you-go, requiring investment only in step with incremental demand. It is one or two orders of magnitude cheaper than building a dedicated, centralized hydrogen production and delivery system from scratch: A nationwide system of decentralized hydrogen sources could be built for $4.1 billion even if *none* of these sources were being built anyway to support the fuel cells in buildings[43], as many actually could be. And vibrant competition between gas- and electricity-derived hydrogen, based on the large and expanding range of fungible sources of both gas and electricity, will exert downward pressure on the prices of hardware and hydrogen. Such competition at a fundamental level is more important and valuable than the narrower forms of competition often invoked by advocates of "fuel flexibility"—a euphemism for "continued dependence on liquid hydrocarbons," in whose name the breakthrough advantages of direct-hydrogen fuel cells are often proposed to be sacrificed.

Aggregation to bulk hydrogen supply

The bigger the total hydrogen market becomes, the more interested the energy industries will become in serving it, expanding bulk hydrogen from an onsite reagent in refineries and petrochemical plants into an offsite commodity. Though offsite shipment, typically in pipelines, may require special arrangements, many existing natural-gas networks appear to be adaptable for this purpose[44]; and if the construction even of special new pipelines, a routine commercial transaction, is justified by the market value of natural gas, then it should be all the more justified by the market value of hydrogen, which can be used far more effectively.

An especially attractive commodity-market opportunity is to reform natural gas at the wellhead, where a large plant can efficiently strip out the hydrogen for shipment to wholesale markets. Professor Robert H. Williams of Princeton University points out[45] that the other product of the separation process, carbon dioxide, could then be reinjected into the gasfield (a common practice today in oilfields), adding pressure that would help recover about enough additional natural gas to pay for the reinjection. The carbon would then be safely sequestered in the gasfield, which can typically hold about twice as much carbon in the form of CO_2 as it originally held in the form of natural gas. The world's abundant resources of natural gas—more than a century's worth—could thus be cleanly, efficiently, and profitably used in fuel-cell vehicles, and in fuel-cell-powered buildings and factories, while reducing the threat to the earth's climate.[46] The hydrogen provider could be paid three times: for the shipped hydrogen, for the enhanced recovery of natural gas (often about enough to pay for the reinjection), and potentially a third time, under future Kyoto Protocol trading or other such arrangements, for sequestering the carbon. This triple profit opportunity, among other value propositions, is already leading several major energy companies to move aggressively into the hydrogen business.

Using electricity to split water to make hydrogen can also be climatically benign if the electricity comes from such renewable sources as solar cells or windfarms—intermittent sources whose economic value would be greatly enhanced by energy storage in the form of hydrogen. One of the biggest renewable energy sources is also the oldest: Old-fashioned hydroelectric dams, like those in the Pacific Northwest and the Tennessee Valley, could make manyfold higher profits if they operated as "Hydro-Gen" plants—using their electricity to make hydrogen to sell as a premium vehicular fuel—than if they kept on selling electricity into an ever more crowded bulk market. This is because fuel-cell cars could use hydrogen at least 2.5–3.5 times more efficiently than today's cars use gasoline. Hydrogen priced to compete at the wheels with $1.25-a-gallon ($0.33/L) gasoline can therefore fetch a far higher value than its raw energy content would imply. In fact, that value is equivalent to selling the electricity used to make the hydrogen at a price about 5–7 times higher than Pacific Northwest dams can actually get for their electricity today.[47] They can thus make far more money by selling not electricity but hydrogen—in effect, shipping each electron with a proton attached. In places like Europe and Japan, where taxed gasoline prices are commonly 3–4 times U.S. levels, this argument is even more compelling.[48] The more the hydrogen is sold, the more its climatically benign bulk production—in Hydro-Gen plants, windfarms, natural gasfields, biofuels, etc.—will expand too.[49]

Implications

This combination of technologies can thus ameliorate, at a profit, close to two-thirds of America's carbon-dioxide emissions[50] while improving mobility, safety, fun, and comfort. Retail price competition will be strong, because at least four main ways to make hydrogen—upstream and downstream, from electricity (especially renewable electricity) and from natural gas—will all be vying for the same customers. We will be betting not on the supply or price of a single fuel such as oil, but on the entire, expanding, and highly dynamic portfolio of ways to make cheap electricity and gaseous fuels.

Practical application of this strategy will require quantitative, site- and region-specific analysis of such issues as the population of buildings suitable for early conversion to fuel cells, those buildings' best hydrogen sources, technical and institutional arrangements for hydrogen-appliance/parked-vehicle interfaces, distributed benefits, Hydro-Gen-suitable dams (*e.g.*, near hydrogen-ready pipelines), pipeline and gas-distribution conversion details, and institutional requirements to provide the best match between fuel-cell and hydrogen investors or operators and the allocation of distributed, environmental, and other benefits. But despite the diversity and complexity of these remaining issues, no breakthroughs are required: The needed technology already exists.

Even without fuel cells, successful Hypercars will ultimately save as much oil as OPEC now sells, making gasoline prices both low and less relevant.[51] Between Hypercars and other new ways to displace oil at lower cost in each of its main uses today, oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices.[52] Like most of the coal and all of the uranium now in the ground, most oil will probably become no longer worth extracting—good mainly for holding up the ground.

The implied shift from oil and electricity to hydrogen as an increasingly dominant energy carrier has equally important implications for vehicle and fuels strategy. The key issue is whether to deploy extremely efficient (≤2 L/100 km) cars as a matter of urgency. Early signs can already be seen that dramatically more efficient vehicles will soon be entering the marketplace, but helping this to happen faster and more aggressively could be highly consequential. Without such hydrogen-ready cars, the very low on- and off-vehicle costs of a direct-hydrogen fuel-cell propulsion system would become unavailable. That lack, in turn, would lock in extra capital costs on the order of $1+ trillion for the next car fleet and its liquid fueling infrastructure[53]; would lock out a highly diverse portfolio of vigorously competing fuel sources (*i.e.*, the hydrogen production portfolio), perpetuating dependence on a narrower, less secure, and less competitive supply base; and would greatly retard the evolution of an affordable, effective, and benign fuel-cell- and hydrogen-based energy system. Thus the cost of not adopting the rapid commercialization strategy is the major delay and compromise of competitive advantage. But starting aggressively down the hydrogen path offers the full benefits of the rapid commercialization of fuel-cell vehicles and the promise, at last, of a more sustainable transportation and electricity system.

Rocky Mountain Institute
1739 Snowmass Creek Road
Snowmass, Colorado 81654-9199, USA, www.rmi.org
1 970 927-3128, FAX -4178, ablovins@rmi.org, bdw@rmi.org

Acknowledgements

Our intellectual debt to our colleagues at Directed Technologies, Princeton University, and Rocky Mountain Institute's Hypercar Center will be clear from the references. This research was supported by grants from W. Alton Jones Foundation, the Compton, Energy, Joyce, and Surdna Foundations, and Rockefeller Financial Services. This paper is adapted and expanded from a portion of Chapter 2 of Paul Hawken, Amory Lovins, and Hunter Lovins's autumn 1999 book *Natural Capitalism: Creating the Next Industrial Revolution* (Little, Brown & Co., New York).

References

Bain, A. 1997: "The Hindenburg Disaster: a Compelling Theory of Probable Cause and Effect." *Procs. 8th Annual U.S. Hydrogen Meeting,* Alexandria VA, National Hydrogen Association, 11–13 March, pp. 125–128.

Brooke, L. 1998: "Composite Crusader," pp. 61–63, *Automotive Industries*, September.

Brylawski, M. & Lovins, A.B. 1995: "Ultralight-Hybrid Vehicle Design: Overcoming the Barriers to Using Advanced Composites in the Automotive Industry," 28 March paper to 41st International Symposium and Exhibition, Society for the Advancement of Material and Process Engineering (SAMPE), Anaheim CA, preprint, RMI Publication #T95-39, www.rmi.org.

Brylawski, M. & Lovins, A.B. 1998: "Advanced Composites: The Car is at the Crossroads," paper to 43rd International Symposium and Exhibition, SAMPE, Anaheim CA, 31 May–4 June 1998, preprint, RMI Publication #T98-1; in press at *SAMPE J.*, March/April 1999.

Cramer, D. & Brylawski, M. 1996: "Ultralight-Hybrid Vehicle Design: Implications for the Recycling Industry," *Procs. Soc. Plastics Engineers Division's 3rd Annual Recycling Conference*, Chicago, 7–8 November, Rocky Mountain Institute Publication #T96-14, www.rmi.org.

Cumberford, R. 1996: "New cars for the new millenium," *Automobile* **11**(7), Oct., and "Lightness is all," *id.* **11**(8), Nov., both reprinted as RMI Publication #T96-13.

Derby, R. 1998: "Unleashing fuel cells' Holy Grail," *Fuel Cells Bulletin* **1**(3):6–8, Dec.

Directed Technologies, Inc. 1997: "Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System for Transportation Applications: Hydrogen Vehicle Safety Report," prepared for U.S. Department of Energy by Ford Motor Co., Dearborn MI 48121, DOE/CE/50389-502, May.

Fox, J. & Cramer, D. 1997: "Hypercars: A Market-Oriented Approach to Meeting Lifecycle and Environmental Goals," Society of Automotive Engineers (SAE) Paper No. 971096, Rocky Mountain Institute Publication #T97-5, www.rmi.org.

James, B.D., Baum, G.N., & Kuhn, I.F. Jr. 1994: *Technology Development Goals for Automotive Fuel Cell Power Systems*, August final report #ANL-94/44 to Argonne National Laboratory, Directed Technologies, Inc., Arlington VA.

James, B.D., Baum, G.N., Lomax, F.D. Jr., Thomas, C.E., & Kuhn, I.F. Jr. 1996: *Comparison of Onboard Hydrogen Storage for Fuel Cell Vehicles*, prepared for Ford Motor Company by Directed Technologies, Inc., Arlington VA, May.

James, B.D., Thomas, C.E., Baum, G.N., Lomax, F.D. Jr, & Kuhn, I.F. Jr. 1997: "Making the Case for Direct Hydrogen Storage in Fuel Cell Vehicles," *Procs. 8th Ann. U.S. Hydrogen Mtg.*, Alexandria VA, National Hydrogen Association, 11–13 March.

Lenssen, N. 1995: *Local Integrated Resource Planning: A New Tool for a Competitive Era*, Strategic Issue Paper IV, E SOURCE, Boulder CO 80301, www.esource.com.

Lomax, F.D. Jr., James, B.D., & Mooradian, R.P. 1997: "PEM Fuel Cell Cost Minimization Using 'Design For Manufacture and Assembly' Techniques," *Procs. 8th Annual U.S. Hydrogen Meeting*, Alexandria VA, National Hydrogen Association, 11–13 March, pp. 459–468.

Lovins, A.B. 1996a: "Hypercars: The Next Industrial Revolution," *Procs. 13th International Electric Vehicle Symposium* (Osaka), October, Rocky Mountain Institute Publication #T96-9, downloadable from www.rmi.org.

Lovins, A.B. 1997: "Auto Bodies Lighten Up," *Technology Review*, May/June, p. 6–8.

Lovins, A.B. 1998: "Putting Central Power Plants Out of Business," address to Aspen Institute Energy Forum, 7 July, RMI Publication #E98-2, http://redtail.stanford.edu/seminar/presentations/lovins1/sld001.htm.

Lovins, A.B., Brylawski, M.M., Cramer, D.R., and Moore, T.C. 1997: *Hypercars: Materials, Manufacturing, and Policy Implications*, 2nd ed., March, 317 refs., The Hypercar Center, Rocky Mountain Institute, www.rmi.org; front matter, RMI Publication #T96-7 (28 pp.), downloadable from www.hypercar.com.

Lovins, A.B. & Lehmann, A. 1999: *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*, proprietary strategic study, in press, Rocky Mountain Institute, Snowmass, CO 81654-9199, www.rmi.org.

Mark, J. 1997: "Environmental and Infrastructure Trade-Offs of Fuel Choices for Fuel Cell Vehicles," SAE-972693, Future Transportation Technology Conference, San Diego, 6–8 August, Society of Automotive Engineers.

Mascarin, A.E., Dieffenbach, J.R., Brylawski, M.M., Cramer, D.R. & Lovins, A.B. 1995: "Costing the Ultralite in Volume Production: Can Advanced Composite Bodies-in-White Be Affordable?," International Body Engineering Conference, Detroit, 1 Nov.; corrected 31 Aug. preprint, Rocky Mountain Institute Publication #T95-35, downloadable from www.rmi.org.

Ogden, J., Steinbugler, M. & Kreutz T. 1997: "Hydrogen as a Fuel for Fuel Cell Vehicles: a Technical and Economic Comparison," *Procs. 8th Annual U.S. Hydrogen Meeting*, Alexandria VA, National Hydrogen Association, 11–13 March, p. 469–506.

Moore, T.C. 1996: "Tools and Strategies for Hybrid-Electric Drivesystem Optimization," SAE Paper No. 961660, Society of Automotive Engineers Future Transportation Technology Conference, Vancouver BC, Rocky Mountain Institute Publication #T96-12, www.rmi.org.

Moore, T.C. 1996a: "Ultralight Hybrid Vehicles: Principles and Design," *Procs. 13th International Electric Vehicle Symposium* (Osaka), October, Rocky Mountain Institute Publication #T96-10, downloadable from www.rmi.org.

Moore, T.C. 1997: "HEV Control Strategy: Implications of Performance Criteria, System Configuration and Design, and Component Selection," *Procs. Inst. Electrical and Electronics Engineers (IEEE), Control Systems Society 1997 American Control Conference*, Albuquerque NM, 4–6 June, Rocky Mountain Institute Publication #T97-7.

Moore, T.C. and Lovins, A.B. 1995: "Vehicle Design Strategies to Meet and Exceed PNGV Goals," *SAE (Society of Automotive Engineers) Future Transportation Technology Conference*, 4 August, Costa Mesa CA, SAE Paper No. 951906, Rocky Mountain Institute Publication #T95-27, www.rmi.org.

President's Council of Advisors on Science and Technology (PCAST) 1997: *Federal Energy Research and Development for the Challenges of the Twenty-First Century*, Report of the Energy Research and Development Panel, 5 November.

Thomas, C.E., James, B.D., & Lomax, F.D. Jr. 1997: "Market Penetration Scenarios for Fuel Cell Vehicles," *Procs. 8th Ann. U.S. Hydrogen Mtg.*, Arlington VA, National Hydrogen Association, 11–13 March; Directed Technologies, Inc. (Arlington, VA 22203, 703/243-3383, FAX -2724).

Thomas, C.E., Kuhn, I.F. Jr., James, B.D., Lomax, F.D. Jr., & Baum, G.N. 1998: "Affordable Hydrogen Supply Pathways for Fuel Cell Vehicles," *Int. J. Hydrogen Energy* **23**(6):507–516, June.

Thomas, C.E., James, B.D., Lomax, F.D. Jr., & Kuhn, I.F. Jr. 1998a: "Fuel Options for the Fuel Cell Vehicle: Hydrogen, Methanol or Gasoline?," Fuel Cell Reformer Conference, Diamond Bar CA, South Coast Air Quality Management District, 20 November.

Williams, R.H. 1996: "Fuel Decarbonization for Fuel Cell Applications & Sequestration of the Separated CO_2." Research Report No. 295, January, Princeton University Center for Energy & Environmental Studies.

Williams, B.D., Moore, T.C., & Lovins, A.B., 1997: "Speeding the Transition: Designing a Fuel-Cell Hypercar," *Procs. 8th Annual U.S. Hydrogen Meeting,* Alexandria VA, National Hydrogen Association, 11–13 March, Rocky Mountain Institute Publication #T97-9, www.rmi.org.

Notes

[1] For example, a 1992 A.D. Little study estimated that a from-scratch bulk hydrogen supply infrastructure sufficient for 25 million cars would require about $95 billion of investment, or $3,800 per car. This antiquated result is still being quoted, *e.g.* in the Epyx article in the December 1998 *Fuel Cells Bulletin* (Derby 1998).

[2] Often but imprecisely used interchangeably with "reformer," a fuel processor comprises a thermochemical (often catalytic) reformer that extracts the needed hydrogen from a hydrocarbon fuel, plus cleanup stages to remove carbon monoxide, sulfur, and any other impurities that could poison the fuel cell's catalyst.

[3] Uniquely, methanol can be reformed to hydrogen at only 260°C rather than the ~600–900°C required for gasoline, ethanol, methane, or other hydrocarbons (Thomas *et al.* 1998a). Methanol also enjoys a short-term global surplus of production capacity sufficient to run about 1.5–2 million relatively inefficient fuel-cell cars (*id.*). However, methanol raises potentially offsetting issues of toxicity and materials compatibility.

[4] Thomas *et al.* 1997, 1998, 1998a, Williams *et al.* 1997, Ogden *et al.* 1997, Mark 1997. The gasoline-to-wheels efficiency can even be slightly lower than that of vehicles with combustion engines, and the capital cost is much higher (Thomas *et al.* 1998).

[5] Successful development of alkaline, high-temperature solid-oxide, or other types of fuel cells would probably not substantially alter our logic. The arguments might change with regard to cars if direct-methanol fuel cells were dramatically improved, but they look uncompetitive with direct-hydrogen PEM fuel cells, at least initially. In the longer term they could get "locked out" by hydrogen's early adoption.

[6] Cumberford 1996, Brooke 1998, Lovins 1996, Moore 1996, 1996a, 1997, Moore & Lovins 1995, Mascarin *et al.* 1995, Brylawski & Lovins 1995, 1998, Lovins, Brylawski, Cramer, & Moore 1997, Cramer & Brylawski 1996, Fox & Cramer 1997.

[7] Williams *et al.* 1997 show a ~4–5-fold range based intentionally on more conservative technical assumptions for a 5–6-passenger sedan. Further reductions in platform mass, drag, and other parameters, and many variants in vehicle type, are possible. The extent of such improvements needs empirical clarification.

[8] Compared with ~40–80 kW for the somewhat improved illustrative aluminum-intensive sedan considered by Thomas *et al.* 1998a. Although many specific designs are possible, some of the fuel cell's output electricity would typically be stored temporarily in a relatively small and lightweight "load-leveling device" or LLD. This buffer-storage device smoothes out temporary fluctuations between the rates at which power is generated and required, decoupling the power plant from the demands of driving and thus allowing the power plant to become smaller. LLDS also can be used, via a process called regenerative braking, to store the energy that would otherwise be dissipated as heat by the brakes. A load-leveling device can use any of at least four demonstrated technologies:

- a high-powered battery that weighs and costs less than a tenth as much as the half-ton of batteries that give a battery-electric car its driving range, because while it must accept and deliver energy rapidly, it needs to store only a few percent as much energy;
- an ultracapacitor, which stores electric charge on rolls of foil separated by an insulator (such a device runs today's portable computers while their batteries are being swapped);
- a superflywheel, which magnetically exchanges energy with a small carbon-fiber rotor spinning extremely rapidly and almost frictionlessly on magnetic bearings in a vacuum; or
- a reversible fuel cell. Doing double duty, part or all of the fuel-cell stack that powers the car could be made reversible at a modest (and recently decreasing) size and efficiency penalty. Within its thermal envelope, it could in principle provide in fuel-cell mode roughly three times its normal output rating for short periods if supercharged with oxygen saved from reverse (electrolytic) operation.

The choice among these technologies, or combinations of them, is not important to success. Indeed, a hybrid-electric car can work quite well without an LLD. However, including a load-leveling device can shift the absolute and relative cost and performance of fuel-cell propulsion systems, as illustrated by Thomas *et al.* 1998a and Williams *et al*. 1997.

[9] Williams *et al.* 1997.

[10] This point is frequently misunderstood: The literature is full of statements that gaseous hydrogen tanks are far too heavy and bulky to be feasible for cars. However, because hydrogen could propel a fuel-cell Hypercar four or more times as efficiently as gasoline, very little hydrogen would provide a long range. The 345-bar (34.4-MPa or 5,000-psig) filament-wound-carbon, metallized-polyester-film-lined tank designs pioneered by Fred Mitlitsky at Lawrence Livermore National Laboratory (James *et al.* 1994, 1996, 1997) would be highly suitable. Williams *et al.* 1997 offer a Taurus-class Hypercar design example whose 4.65-kg H_2 tank has 2.5-fold larger volume and 2-fold lower mass than a gasoline tank of equivalent range (over 900 km). Thomas *et al.* 1998a illustrate a less efficient (~40–80-kW_e) fuel-cell sedan that nonetheless packages 3.63 kg of H_2. Preliminary tests, *e.g.* by Ford, indicate that such tanks can be made with standard techniques at affordable costs, are extremely difficult to cause to fail (they could be one of the strongest parts of the car), and tend to fail gracefully. Thomas *et al.* 1998a also correctly note that liquid-hydrogen storage, a technique favored by BMW, is feasible with existing technology, though we consider it unnecessary.

[11] Further, because of their high efficiency at part load, fuel cells do better under typical driving conditions than a simple comparison of conversion efficiencies would indicate—especially when compared to a typical Otto engine, which on average is only about half as efficient as its peak value under such conditions (Williams *et al.* 1997).

[12] One of us (ABL) estimates ~$5 billion; an industry panel at the Los Angeles Auto Show's Clean Car Conference on 29 December 1998 estimated comparable or higher values.

[13] A periodically updated chronology is posted at www.hypercar.com, which provides >100 pages of nonproprietary explanations of the concept.

[14] Williams *et al.* 1997.

[15] The cost penalty is well established, both onboard the car and for a total infrastructure system, in Thomas *et al.* 1998a.

[16] Several independent studies (*e.g.*, Lomax *et al.* 1997) have used standard industrial engineering techniques to calculate costs around $20–35/kW for the PEM fuel-cell stack at high production volumes. Its accessories could become very, though not negligibly, cheap with low-pressure designs, blow-molded plastic plumbing, mass-produced power electronics, and simplified management of heat, humidity, and water chemistry.

[17] However, this conclusion, though plausible and helpful, is not essential to our argument. The key point is that the automotive and buildings markets are *both* so big that once either one starts to happen, it will quickly make the other happen too by increasing volume and cutting cost. For present purposes, the many differences of detail between fuel cells optimized for mobile and for stationary uses are less important than their similarities.

[18] Widely quoted efficiency figures around 30-odd to 50 percent assume the fuel cell is fed not pure hydrogen but the more dilute and impure reformate gas converted from a hydrocarbon fuel, and often include also the conversion losses in the fuel processor.

[19] Other useful functions can include water heating and space-cooling reheat. The air-conditioning functions can use various combinations of absorption and desiccant cycles, both of which can work well at 70°C (*e.g.*, Yazaki machines), and may be combined with, for example, indirect evaporative cooling. A considerable fraction of U.S. commercial buildings' air-conditioning capacity is slated for replacement in the next decade or so because of age and the need for CFC displacement.

[20] Obviously, liquid fuels would become potentially interesting reformer feedstocks only if natural gas were not locally available, so that (for example) LPG or biofuels had to be substituted.

[21] For illustration, even an \$800/kW$_e$ fuel-cell system, at a 15%/y fixed charge rate, would incur a capital charge of only 2.7¢/kWh at a 50% capacity factor. Alternatively, the net electrical output efficiency of a PEMFC using reformed methane is often quoted at or above 40% (LHV), often with neither heat recovery from the stack to the reformer nor pressure recovery from the stack's hydrogen input and stack output to the air compressor; with both, the best technology is now ~50%. At 50% conversion efficiency, natural gas at \$3.7/GJ or \$4/10^3 ft^3 would produce electricity at 5.5¢/kWh: 2.7¢/kWh for the fuel plus 2.7¢/kWh for the cost of a relatively expensive early fuel-cell system at ~\$800/kW, plus a nominal 0.1¢/kWh for O&M. This would undercut typical commercial-sector U.S. electricity tariffs (averaging 7.6¢/kWh in 1997) by 28%, even with *no* thermal credit and no allowance for the improved power quality and reliability or for other distributed benefits.

[22] Lovins & Lehmann 1999, representing the capital and operating costs and the losses of the transmission and distribution systems for the average customer at the average hour. Obviously the actual costs, both total and marginal, depend on who, where, and when.

[23] Such deferral of grid investment is among the roughly 75 important "distributed benefits" available to improve fuel cells' investment value (Lovins & Lehmann 1999). Many others can add important extra value, and most will be increasingly valued and recognized within the new structures, skills, and institutions emerging within the context of the restructuring of the electricity industry. Of course, realizing the profit from avoided grid investments requires institutional arrangements to recognize this value and, if necessary, to reallocate it from the distribution utility to other actors.

[24] Lenssen 1995. In emerging competitive markets, the value of such local grid support may become reflected in "decongestion rents." Some customers, too, already have their own incentives to avoid investments in renewed or expanded service-entrance facilities such as substations or stepdown transformers.

[25] Lovins & Lehmann 1999.

[26] The interconnection device could be provided at reasonable cost by the landlord, a gas or electric utility, or a third-party entrepreneur. Southern California Edison's EV subsidiary installs Hughes inductive-paddle rechargers, whose electric capacity is broadly comparable, for ~\$50/kW. This might at first seem significant, but in fact it is a small fraction of the typical value of distributed benefits. Obviously, the interconnection becomes more commercially attractive if the distributed benefits can be properly captured, if they are captured mainly by those making the investments, and if the institutional arrangements are kept simple and transparent.

[27] The fuel cell would therefore need to be designed for a much longer operating life than is normal in cars, but this is not unduly difficult if it is consistently fed high-quality hydrogen. The marginal cost of such design would be well compensated by the extra value created. Technologies for making the hydrogen pure enough are well established, as are inexpensive controls to protect the stack and inverter from electrical anomalies.

[28] For illustration, a 20-kW "mobile power plant" earning an average of, say, 5¢ gross or 2¢ net of fuel cost per kWh—remember, the car could often generate during peak hours and earn real-time pricing premia—for an average of, say, 15 h/d, or 65% of its nominal parking time, would return $2,190 net per year, or 59% of the total depreciation and financing cost of the average 1994 U.S. passenger car. A light vehicle with a bigger fuel-cell stack could earn twice that much. Obviously, the surplus, and the costs of capturing it, would actually be shared among a number of actors in proportion to their market power.

[29] 150 million light vehicles times a minimum capacity of 20 kW_e—the average could be substantially higher—yields 3 TW_e, *vs.* summer-1997 U.S. peak capability of 0.78 TW and 1996 noncoincident peak load of 0.62 TW (neither of which reflects the ~14% onpeak grid loss).

[30] Bain, 1997; Bain, Addison: Personal communication, 1 November 1999.

[31] Directed Technologies, Inc. 1997.

[32] James *et al.* 1997. Further, a fuel-cell Hypercar could travel roughly 200 km on 1 kg of hydrogen: A Taurus-class Hypercar was calculated to drive roughly 925 km fueled by 4.65 kg of hydrogen (Williams *et al.* 1997).

[33] Though this approach can doubtless be improved, it gravely weakens or negates many of the fuel cell's original advantages: Thomas *et al.* 1997, 1998, 1998a, Ogden *et al.* 1997, Williams *et al.* 1997, Mark 1997. Further, reformers will always work better, and have an enormously higher capacity factor, offboard the vehicle. Nonetheless, many automakers are pursuing the onboard-fuel-processor concept, presumably because they assume inefficient cars (hence too-large hydrogen tanks), safety problems, and/or infrastructure problems.

[34] President's Council of Advisors on Science and Technology (PCAST) 1997 at 6-34.

[35] Ogden *et al.* 1997, Thomas *et al.* 1997, 1998a. Although natural gas reformation is generally assumed to be the cheapest option, if offpeak retail electricity costs only ~1.5–3 cents per kilowatt-hour, as it now does in many parts of the U.S., using it to split water could cost less than locally reforming natural gas for small numbers of fuel-cell vehicles: Thomas *et al.* 1998, 1998a. Electrolysis could therefore initially be deployed faster if initial vehicular hydrogen markets were small, but vehicle fleets or, of course, fuel-cell systems in buildings could favor small steam methane reformers.

[36] Thomas *et al.* 1998a.

[37] *Id.*

[38] Or at your house or apartment, which might offer more opportunities for thermal integration. The workplace example is given to capture the value of daytime (*i.e.*, typically onpeak) generation.

[39] Even when far from the office, you needn't worry about running out of hydrogen because your hydrogen-fuel-cell car could have a longer driving range than a conventional car, and its navigation screen could display every available hydrogen source, updated wirelessly. In a pinch, one can imagine that an electrolyzer (standalone or in a reversible stack) could slowly make hydrogen onboard when plugged into any electric outlet. Alternatively, a tow truck could provide hydrogen from a tank or from its own reversible fuel cell or electrolyzer—the hydrogen equivalent of jumper cables.

[40] Lovins 1998. Onsite storage of compressed hydrogen is straightforward, although updating of regulations is necessary. In general, current regulations, meant for natural gas, assume metal tanks subject to corrosion and cracking, and are overly conservative for the very different engineering details of composite hydrogen tanks.

[41] Such hydrogen appliances could even end up in individual garages—better than schlepping one around in your car, and providing battery cars' overnight refueling advantage. Electrolyzer Corporation of Canada, for example, is developing just such an electrolyzer-and-compressor device for home use.

[42] This strategy should prove easier, more profitable, and useful for longer than creating a recharging infrastructure for battery-electric cars or adapting the existing gasoline infrastructure to methanol. Both of these would probably prove to be short-lived transitional investments, unless perhaps direct-methanol fuel cells prove attractive, and both lack the long-term flexibility that lets a direct-hydrogen strategy adapt readily to new sources of hydrogen.

[43] Assuming 18,000 stations each able to supply 1,000 relatively conventional (~40–80-kW_e) fuel-cell vehicles—an offboard investment of $230 per vehicle: Thomas *et al.* 1998.

[44] Older existing pipelines originally meant for "town gas," the hydrogen-rich synthetic predecessor of natural gas, can be suitable. Middle-aged pipelines without the proper metallurgy and seals could often be retrofitted *in situ* with metallized composite liners. In any case, natural-gas rights-of-way would be available for conversion. As in all other contexts, economic comparisons of such network conversions should be made not per joule of methane or hydrogen carried, but per unit of *service* (such as vehicular traction) delivered; otherwise hydrogen is unfairly penalized by not properly counting its extremely high end-use efficiency.

[45] Williams, R.H. 1996.

[46] The same would be true of renewable sources of methane—anything that rots—if the CO_2 were sequestered.

[47] One gallon priced at $1.25 contains 125 kBTU or 132 MJ, enthalpically equivalent to 36.6 kWh of electricity priced at 3.4¢/kWh. However, the 2.5–3.5-fold greater efficiency of converting each J of hydrogen into vehicular traction, compared with a J of gasoline (*i.e.*, ~50% system efficiency in a fuel-cell car *vs.* 15–20% in an Otto-engine car), makes this price functionally equivalent to 8.5–12¢/kWh. That is so much larger than the current Pacific Northwest bulk electricity price of 1.6¢/kWh that the spread could more than cover the cost of electrolysis and hydrogen delivery.

[48] This is bad news for aluminum smelters, which now often enjoy preferential access to very cheap hydropower under old contracts that will represent an increasingly severe opportunity cost. However, it might be good news for anadromous fish if hydrogen storage could be large enough to control seasonal water flows for their benefit.

[49] New, cheaper ways to use solar electricity to obtain hydrogen from water are rapidly emerging too. So are methods that use light instead of electricity, imitating photosynthesis, but so far these are only in the laboratory.

[50] Only the road-vehicle portion of transportation's emissions, of course, but fuel cells in buildings and industry would also displace much of the fossil fuel now burned for space, water, and process heating.

[51] This probably won't trigger an orgy of driving: other costs in money, time, and frustration won't greatly change.

[52] Lovins 1998.

[53] If one multiplies the per-vehicle costs in Thomas *et al.* 1998a times the world's fleet of a half-billion light vehicles, which is growing by about 5% a year.