Pergamon

Renewable Energy, Vol. 10, No. 2/3, pp. 471–479, 1997

Printed in Great Britain
0960–1481/97 $15.00+0.00

PII: S0960–1481(96)00106–1

HYPERCARS: SPEEDING THE TRANSITION TO SOLAR HYDROGEN

Adapted from Lovins *et al.* 1996 by BRETT D. WILLIAMS
The Hypercar Center, Rocky Mountain Institute
1739 Snowmass Creek Road
Snowmass, Colorado 81654-9199, USA
+ 1 970 + 927-3851, fax + 1 970 + 927-4178, bwilliam@rmi.org, http://www.rmi.org

ABSTRACT

A discontinuous transformation now underway in automotive technology may accelerate the transition to transportation powered by solar hydrogen. Even using internal-combustion engines, ultralight, ultraslippery, advanced-composite, hybrid-electric "hypercars" can be severalfold lighter and lower-drag than present steel cars; many times more efficient; and over two orders of magnitude cleaner; yet equally safe, sporty, comfortable, durable, beautiful and (probably) affordable. The required design integration is technically and culturally difficult. Yet important manufacturing advantages permit a free-market commercialization strategy impelled not by government mandates or subsidies but by manufacturers' quest for competitive advantage and customers' desire for superior cars.

Proton-exchange-membrane fuel cells (PEMFCs) are promising even for heavy and high-drag hybrid cars because they can convert hydrogen into traction severalfold more efficiently than today's drivelines convert gasoline. But hypercars would need significantly fewer kilowatts of power, and could therefore adopt PEMFCs earlier—before their specific cost, mass, and volume mature. The resulting high production volumes could quickly cut PEMFCs' costs enough to displace a significant portion of thermal power stations, either in stationary applications or by plugging in parked hypercars. This potential break-though for PEMFCs is one new stimuli to early emergence both of distributed electric utilities and of hydrogen fuel as a major output of renewable energy sources.

KEYWORDS

Hydrogen; proton-exchange-membrane fuel cells; hypercars; light vehicles; hybrid-electric vehicles; distributed resources; power generation.

BACKGROUND

The following discussion is based on previous work by Rocky Mountain Institute on the hypercar concept. For brevity, hypercars *per se* are not discussed here, but can be summarized as follows: A "leapfrog" design concept (RMI, 1991–present) a "hypercar" artfully integrates an advanced-composite, ultralight body-in-white with a hybrid-electric driveline, resulting in a car that is severalfold lighter and lower-drag than present steel cars; many times more efficient; and over two orders of magnitude cleaner; yet equally safe, sporty, comfortable, durable, beautiful and (probably) affordable. The required design integration is technically and culturally difficult. Yet important manufacturing advantages permit a free-market commercialization strategy impelled not by government mandates or subsidies but by manufacturers' quest for competitive advantage and customers' desire for superior cars. Detailed discussion on hypercars (Lovins 1995; Moore and Lovins 1995; Lovins *et al.* 1996) is available from Rocky Mountain Institute at the address printed above.

SPEEDING THE TRANSISTION

Hypercars' design would make automobiles far more practical users of two classes of fuels that usually burn cleaner than gasoline:

- alternative liquid fuels (notably biofuels) and
- gaseous fuels, ranging from very clean compressed natural gas (CNG) to solar hydrogen.

This shift could greatly reduce or even eliminate both the air pollution and the climatic risk of cars. Except in special fleet-vehicle cases, however, gaseous fueling is seldom attractive today, because

- the cars themselves are so inefficient that a large, heavy, and costly tank is needed to carry enough fuel for substantial range;
- their more frequent refueling may require more ubiquitous and hence more costly refueling infrastructure; and
- the fuel-cell stack (the ideal way to convert energy from gases to electricity) required to propel such heavy cars would itself be excessively heavy, bulky, and expensive.

Hypercars can systematically remove each of these obstacles.

Hypercars Make Compressed Gaseous Fuels Practical

Hypercars would complement and strengthen existing CNG- and hydrogen-related R&D and deployment in two important ways:

1. Hypercars would ensure that the dominant car design by early in the next century is so efficient, typically ~4–10 times better than today's norm, that it makes fueling with energy gases

- technically convenient because even a relatively small, light, cheap tank would run the car for a long distance and need only infrequent refueling and
- as much as an order of magnitude less sensitive to the price of fuel—*i.e.*, if the car uses only a tenth as much fuel, the fuel will cost the same per *kilometer* even if it costs ten times as much per *megajoule*—thus making the economics of hydrogen sources, for example, far less critical to hydrogen's market success.

Hypercars could achieve these results without compromise. On the contrary, they should make the new car design superior in all respects, including costs. This does an end-run around the fuel-price-elasticity debate, and makes rapid market success highly probable.

2. Hypercars would make vehicular fuel cells a far more robust vehicular powerplant option by

- reducing by ~2–5+-fold the kW output capacity, physical size, mass, and cost of the fuel cells *required to run* the car, and
- making fuel cells only *one of many* technical options for the vehicle's onboard powerplant, thus
- providing generous safety margins and multiple technological backstops to fuel-cell development—more good eggs in the compressed-methane-or-hydrogen basket.

In short, hypercars could

- make hydrogen's success as the main or only fuel for road vehicles severalfold less dependent on success in making hydrogen and fuel cells cheaper and in making fuel cells smaller and lighter (similarly for CNG);
- ensure the competitiveness of gaseous automotive fuels even if fuel cells fail to meet their design goals and another form of APU must be substituted—*i.e.*, diversify the APU portfolio suitable for gaseous fuels;
- rely for their success on strong consumer demand for superior performance and features, not on cleanliness or efficiency, and on strong automaker demand for competitive advantage, not on government mandates like ZEV or CAFE; and
- by these means make achievement of a solar-hydrogen (or CNG) road transport sector far more robustly likely.

Depending on how sanguine one is about the likelihood that current efforts will make solar hydrogen a cheap, convenient, and widely available fuel, this complementary approach from the other direction—making the car ideal for hydrogen, not just the other way around—could be considered a selling tool, a vital foundation, or an insurance policy. Either way, it is a sound investment, adding yet another motivation to the commercialization of hypercars.

Hypercars can strongly accelerate mass-production of PEM fuel cells

In autumn 1995, RMI realized that the logic just described has new and important implications when combined with rapid recent progress in proton-exchange-membrane (PEM) fuel cells. These implications may ultimately prove even more important for reshaping the global energy system, and its climatic and other environmental impacts, than hypercars themselves.

Led by Ballard Power Systems[1], with several other firms in hot pursuit, and substantial membrane development efforts by the likes of DuPont and Dow, PEMFC development has lately proceeded with gratifying speed. On 3 October 1995, for example, Ballard announced the achievement, in a joint program with Daimler-Benz AG, of the highest specific power ever acknowledged for PEMFCS—stack-only continuous ratings of 1 kW/l and 700 W/kg fueled with H_2/air, with substantially higher peak ratings.[2] This is more than three times the continuous-rated power density of cells used in Ballard's 1993 Phase II fuel-cell bus, whose entire fuel-cell apparatus fitted into the normal engine compartment, or of Daimler-Benz's 1994 fuel-cell van. It is also about seven times the power density of the better-known 1991–92 Phase I Ballard experimental bus, and about five years ahead of the U.S. Department of Energy's development goals (a significant inhibitor to some firms that believed DOE rather than market intelligence). Daimler-Benz announced in August 1995, based on this progress, its intention to unveil in early 1996 an all-PEMFC vehicle. Customer interest was swift—including the Chicago Transit Authority's decision to launch in autumn 1996 a three-year test of Ballard-fuel-cell buses with a view to converting its entire 2,000-bus fleet. Some other major cities are interested in doing the same, and Ballard is also developing a 100-kW methanol-fueled "fuel cell engine" for buses.

The foregoing logic of using hypercars to hasten the commercialization of hydrogen fuel becomes especially interesting when applied to PEMFCs, because this type of portable fuel cell has physical attributes that could soon permit it to be cheaply mass-produced, perhaps by sticking together roll-to-roll polymer components. Three recent evaluations—by GM's Allison division (Allison 1993), A.D. Little, Inc. (proprietary 1995 personal communications[3]), and Directed Technologies, Inc.[4] (Thomas and Kuhn 1995; James *et al.* 1994; Ira Kuhn, Jr., personal communications 1995)—reflect a growing consensus that at high production volumes, hydrogen/air-fueled PEMFCs using the best technologies in the laboratory in spring 1995 could probably achieve manufacturing costs below \$50 per gross kW_e: specifically, about \$34[5], \$40, and \$22–37/kW respectively.[6] These assessments rely, to varying but significant degrees, on extensive knowledge of proprietary development programs, and the differences between the three findings are immaterial. Several firms have privately announced their intention, widely considered plausible in light of recent progress, to bring competitive PEMFCs to market, probably initially at a few hundred

---

[1] Unit 107, 980 W 1st St., N. Vancouver, BC, Canada V7P 3N4, 604/986-9367, FAX -3262. RMI is grateful to Ken Dircks (Manager, Customer Support) for helpful discussions, most recently at a 31 October 1995 site visit and in a 20 February 1996 phone update.

[2] Keith Prater (Ballard's Vice President of Technology), 604/990-3124, FAX -3262, "SPFC Fuel Cells for Transport and Stationary Applications," 1995. The unpublished test conditions were specified by Daimler-Benz and, though realistic, apparently differed somewhat from Ballard's norms.

[3] Dr. Jeffrey Bentley, Arthur D. Little, Inc., 20 Acorn Park, Room 20/507, Cambridge MA 02140-2390, 617/498-5820, FAX -7114, another very knowledgeable and helpful informant.

[4] Dr. Ira F. Kuhn, Jr. is President of Directed Technologies, Inc., 4001 N. Fairfax Drive, Suite 775, Arlington VA 22203, 703/243-3383, FAX -2724. He kindly provided a briefing on 8 June 1995.

[5] The commonly quoted \$46/kW includes a methanol reformer.

[6] As a quick reality check, high-precision, high-volume metal manufacturing, *e.g.* of automotive engines and transmissions, costs on the order of \$9/kg. Automakers' fuel-cell researchers generally accept that making PEMFCs from highly repetitive and mechanically simple parts should cost at worst about half that much, implying a stack cost around \$6/kW at Ballard's already-achieved but not yet mass-optimized 0.7 kW per stack kg. Balance-of-system should typically have a lower specific cost for mountings, pipes, and valves, higher for power electronics. The order of magnitude for system cost suggests that the tens-of-\$/kW range is perfectly reasonable.

\$/kW, around the end of 1998. Those vendors consider the tens-of-dollars-per-kW target plausible in volume production, based on established principles of manufacturing and materials costing.

Hypercars' distinctive advantage in accelerating the mass-production of PEMFCs comes from their needing only ~10–25 kW of onboard power generating capacity, because their road loads are 2–3-fold lower and most of their peak power requirements are met by the load-leveling device, not the onboard generator. For example, a 5–6-passenger hypercar with acceleration better than and gradability similar to a same-sized Taurus, because it is 2–3-fold lighter and more slippery, would need only ~25 kW of continuous or peak DC power rating from its APU, compared with 104 kW[7] of mechanical shaftpower from the Taurus's internal-combustion engine. A better-optimized 4–5-passenger hypercar could need as little as 10 kW. Thus *hypercars need on the order of 4–10-fold less prime-mover capacity*, and hence, after due correction for driveline efficiency all the way to the wheels, should be manyfold less sensitive to APU *cost per kW*. This unique feature could leapfrog PEMFCs rapidly into high-volume production, hence even lower cost, by making it economically possible to use the fuel cells *at a much earlier stage of their development*—before they become nearly as light, small, and cheap per kilowatt as they will be later.

A conservative comparison of kW requirements emerges from a conceptual design of a Ford Taurus that is assumed to be simply converted into a fuel-cell hybrid, without taking credit for the mass reduction probably resulting (James *et al.* 1994). Such a heavy Taurus-class car requires only 85 kW of fuel cells for comparable performance, and those fuel cells could compete in capital cost with the Taurus's internal-combustion-engine mechanical driveline if they cost no more than ~\$37/kW. But a Taurus-class hypercar needing only 25 kW of fuel cells could then be comparably competitive using PEMFCs that cost ~\$126/kW—several times the cost generally expected from mass-producing good PEMFC technologies whose performance parameters are already demonstrated. A conservatively designed 4–5-passenger hypercar with similar or sportier performance, requiring only ~22 kW of APU continuous rating, could tolerate ~\$143/kW fuel cells. A lighter and lower-drag model with quite high efficiency, requiring only a ~10-kW APU, could then tolerate ~\$315/kW—easily within normal projections for PEMFCs in early volume production. Obviously, PEMFCs could be introduced first in smaller, lighter car models that are most price-tolerant, using their production to build fuel-cell sales and cut costs.

Other important conclusions emerge from the Kuhn group's conceptual design (James *et al.* 1994) for a standard Taurus-class car, converted to a PEMFC hybrid with no improvements in platform physics.[8] Consider such a car fueled with 345-bar hydrogen that is

- electrolyzed, probably using PEMFC technology in reverse, and compressed to 414 bar (6,000 psia) using 2–4 ¢/kWh U.S. retail offpeak electricity in a ~\$4k neighborhood refueling station (hydrogen produced by natural-gas reforming could compete against costlier electricity);
- stored onboard in a filament-wound T-1000 carbon-fiber tank lined with metalized polyester film and already shown empirically to provide excellent safety[9]; and

---

[7] These figures are not directly comparable, not only because the proper comparison is in tractive power delivered to the wheels—though conversion losses in both cases should be similar—but also because the fuel-cell rating is continuous, while the IC engine is designed to produce its rated output for only three minutes at sea level at 20°C. It would therefore require considerably more capacity for such a continuous rating under adverse conditions—a hot, humid summer day, or one at high altitude. Under some circumstances, this increase could be substantial enough so that James *et al.*'s assumption that an 85-peak-electrical-kW fuel cell is equivalent to that 104-peak-mechanical-kW could prove conservative.

[8] Except an unimportant ~10% reduction in mass and in aerodynamic drag (to $C_D = 0.28$, $A = 2.14$ m^2), accompanied by a high $r_0 = 0.0135$ and inefficient accessories. Actually, the powertrain and hence platform mass should be somewhat lower too: James *et al.* (1994) show on p. 1-3 that for a nominal 1,361-kg-curb-mass midsize sedan, the powertrain mass, conventionally ~435 kg (estimated from 1981 technology; OTA's equally undocumented 1990 estimate was 458 kg), would be ~460 kg with a ~1996 PEMFC demonstrator but only ~311 kg with a ~2004 PEMFC production model. Of the difference, 32% is the improved gaseous-hydrogen storage tank, and another 22% a lighter load-leveling device (assumed to be an ultracapacitor). However, no credit is taken in either case for the radically lighter platform mass, lower air and road drag, or lower accessory loads typical of a hypercar. These attributes would of course reduce tractive loads correspondingly. For example, the 5–6-passenger early hypercar modeled in Moore and Lovins (1995) has a curb mass of 700 kg, a gross mass of 1,200 kg, a peak electric busbar power capability of 52 kW, and a total driveline mass of 266 kg. Scaled up to the nearly twice-as-heavy Directed Technologies conceptual design's capability of 85 kW, this driveline mass would scale (assuming a crude and perhaps nonconservative linear approximation) to 435 kg—comparable to the near-term PEMFC using similarly mature technologies.

- filled to the same fuel-plus-tank mass as the original Taurus gasoline tank (though the tank *volume* in such a relatively inefficient car would be nearly 5-fold larger, as discussed below).

Using a ~60% net efficient fuel-cell stack[10], the conceptual design shows that such a car would

- have a longer driving range than the original gasoline-powered IC-engine Taurus;
- have a lower fuel cost per km than the original Taurus burning taxed U.S. gasoline; and
- in volume production, cost less to manufacture.

These impressive findings result from the severalfold higher efficiency of converting gaseous hydrogen rather than gasoline into tractive energy: the electricity used to make the hydrogen is a costlier energy carrier, but hydrogen's more efficient use, via the hydrogen-fuel-cell cycle at ~60% net stack efficiency, more than compensates. (Specifically, the fuel cell is nearly twice as efficient as the *peak* efficiency of an ordinary Otto engine, and ~3–4 times as efficient as the *average* efficiency of an Otto engine in a non-hybrid car, integrating over the operating map.)

The lower whole-car capital cost of the Kuhn team's hypothetical PEMFC Taurus is reasonable, too, because the mass-produced fuel cell costs about the same per electric kilowatt as the mass-produced internal-combustion engine costs per shaftpower kilowatt (<$50/kW in both cases). (Of course, the balance-of-drivesystem costs must also be compared.)

The findings just described for a heavy, relatively high-drag Taurus conversion should be all the more true of an *ultralight, ultraslippery* hybrid car requiring severalfold fewer kilowatts of onboard generating capacity to achieve comparable capacity, gradability, and acceleration. Such a platform should also be economically attractive with PEMFCs costing severalfold more than the three above-cited studies' long-term, high-volume projected asymptote of $22–40/kW.

Another surprising feature of pressurized-hydrogen fuel-cell hypercars is their modest tankage requirements. This point is frequently misunderstood: the literature is full of careless statements that gaseous hydrogen tanks are far too heavy and bulky to be feasible for cars. It is true that hydrogen gas, though it has 2.7 times the Lower Heating Value (LHV) energy content of gasoline per unit *mass*, has at a pressure of (say) 170 bar, halfway to full useful discharge from a freshly filled tank's nominal 345-bar pressure, only *0.06* times gasoline's energy content per unit *volume*. However, this does not mean that compressed-hydrogen tanks need be very heavy and bulky, for two reasons:

- that illustrative 345-bar pressure can be tripled if desired without unpleasant consequences (Ira Kuhn, personal communication 8 June 1995), and even more importantly,
- hydrogen consumed in a ~60%-efficient fuel cell can be converted into hypercar traction about eight times as efficiently as gasoline in an ordinary midsize car, or about twice as efficiently as gasoline in a functionally equivalent (conservatively, quadrupled-efficiency) hypercar.[11]

---

[9] Kuhn (personal communication, 8 June 1995) states that in extensive tests, such tanks were crashed, crushed, dropped, shot, burned, and blown up, but failed to produce any consequences as bad as those resulting from comparable assaults on ordinary gasoline tanks. This is largely because the hydrogen tanks fail gracefully (leak-before-break); hydrogen is buoyant; and its low-emissivity flame has no incandescent soot to radiate infrared and so cause burns at a distance. Kuhn also maintains that the same safety conclusion remains valid at tripled pressure (1 kbar, 15 kpsia).

[10] Measured in the lab over the Federal Urban Driving Schedule, the gross PEMFC fuel-to-electricity stack conversion efficiency cited by James *et al.* (1994) was just over 66%—not atypical of current stack development—but parasitic losses for supercharging, gas flow friction, pumping, and cooling must be debited against the gross output. These authors calculate that parasitic air-compression energy would never exceed 10%, more commonly 8%, of gross electric output at peak demand and low hydrogen pressure, falling to 3% at lower demand with a tank full of 345-bar (5-kpsia) hydrogen, because most of the compression energy can be recovered by hydrogen and exhaust-gas turboexpanders. Thus net fuel-cell stack efficiency would be ~60% delivered to the power conditioner and drivemotor.

[11] Based on an approximate comparison between a ~30%-peak-efficiency nominal Otto-engine-plus-generator and James *et al.*'s (1994) ~60% nominal net stack efficiency as described above. In practice, the fuel-cell-*vs.*-conventional-car comparison would be much stronger, both because the Otto engine's efficiency is about halved by map rather than single-point operation in a mechanical-drive IC-engine car, and because the fuel cell's peak efficiency occurs at part-load, offering additional design space for optimizing hybrid operation so as to minimize both cycling and storage. As a first approximation, pending more refined parametric design just beginning at RMI, in Table 1 (opposite) we therefore halve the Moore and Lovins (1995) "Further Optimized" case's combined-city/highway 2.09 l/100 km fuel intensity to 1.05 l/100 km.

Table 1. Illustrative tankage for compressed-hydrogen fuel-cell hypercars

fuel		Gaseous H_2	Gaseous H_2	Gaseous H_2	Gasoline
tank		filament-wound T-1000 C, aluminized polyester film liner, safety factor = 2.25 (current USDOT standard)	same, but safety factor 1.50—stated by James *et al.* (1994) to be the same as is now typically required for critical loadbearing structures in military aircraft and submarines		ordinary automotive tankage, with *no* correction for unusable fuel portion*
design fuel pressure		345 bar, 5 kpsia	345 bar, 5 kpsia	1.03 kbar, 15 kpsia	1.01 bar (1 atm.)
MJ fuel (LHV)		820	820	820	820
kg fuel		6.8	6.8	6.8	18 kg (26 l)
filled tank kg		52	36	~47	~24
filled tank liters (l)		335	325	~163	27+
fuel/filled tank mass ratio		0.13	0.19	0.14	0.75
driving range @ 1.05 l/100 km (see footnote 12)		~2,500 km, ~1,500 mi	~2,500 km, ~1,500 mi	~2,500 km, ~1,500 mi	—
@ 8.84 l/100 km (PNGV benchmark for midsize sedan):	driving range of that 26 l of gasoline	—	—	—	294 km, 182 mi
	l of gasoline to get same range as H_2	—	—	—	219 l
	kg of filled gasoline tank to get same range as H_2	—	—	—	>170 kg
H_2/gasoline ratio of filled tanks for same driving range at their respective nominal car efficiencies	mass	<0.31	<0.21	<0.28	—
	volume	<1.52	<1.48	<0.74	—
	fuel MJ	0.12	0.12	0.12	—

*No corrections are made in this table for the higher percentage of usable fuel available from compressed-hydrogen storage systems than from gasoline systems. For example, James *et al.* (1994) suggest that only 94.7% of 72 liters (~2,241 MJ) of gasoline is usable in a conventional Taurus-class vehicle, mainly because of the need to accommodate the liquid's tilt and slosh in a moving vehicle while keeping the liquid-fuel pump fed. In contrast, the 820 MJ compressed-hydrogen tanks described above can discharge down to the minimum pressure required by the fuel cell plus in-line pressure drop, and hence will have a usable fraction over 99%. Making this correction would improve the hydrogen/gasoline ratios shown, to a degree dependent on the geometry of the gasoline tank.

Table 1, partly drawn directly and partly calculated by RMI from James *et al.* (1994), shows that for the same driving range, depending on the tank safety factor and pressure assumed, even a conservatively designed early hypercar would need a hydrogen tank ranging from about 50% larger to 25% smaller than the traditional sedan's gasoline tank, and weighing ~70–80% *less*.

Even in the left-hand column of figures, using the present officially required U.S. tank safety factor of 2.25 and the relatively modest pressure of a third of a kilobar, the results are impressive. But though the reasons for regulatory conservatism are understandable, that safety factor (ratio of ultimate rupture to design pressure) appears to reflect traditional understanding of metal tanks prone to fatigue, embrittlement, corrosion, and considerable manufacturing variability. Greater experience may well persuade the safety authorities that the advanced-composite tanks analyzed here lack these drawbacks, and that a safety factor around 1.5 is indeed reasonable with careful quality assurance (including nondestructive testing) in materials and mass production, perhaps supplemented by embedded damage or stress sensors.

It is also encouraging that at a 1.5 safety factor, tripling the pressure, as shown in the third column of figures, raises empty-tank mass only 30%, and halves tank volume for the same contained energy (James *et al.* 1994). Better still, at high-volume production (a million tanks per year with carbon fiber at $13/kg), a 2.25-SF cylindrical, spherical-endcaps tank of this type could be plausibly made from ~$484 worth of materials (*id.*), plus minimal fabrication cost. Further compaction of tankage is also possible with liquid hydrogen or with hybrid cryo-pressure storage (*id.*), but seems a needless complication when gaseous hydrogen, requiring no insulation and having no standby boiloff loss, looks so attractive.

Another way to state the compressed-gas tankage results is that because the PEMFC hypercar converts its gaseous hydrogen fuel into traction so efficiently, a fuel tank with about one-third of the 6.8-kg hydrogen capacity assumed above would provide the same driving range that American drivers normally expect from their ~70-l gasoline tank. Alternatively, the sort of hydrogen-tank capacity shown in the table could permit an average U.S. driver to refuel only about every six weeks—possibly a desirable special feature for some market segments. And as for the comparison with battery-electric cars, 500 kg of lead-acid batteries at a nominal 35 Wh/kg yields only 17.5 MWh at full discharge—the same energy produced by a 60%-efficient PEMFC consuming a mere 0.87 kg of hydrogen, or 574 times less mass. Even with the hydrogen tank and fuel cell, the complete hydrogen system would be about 10-fold lighter than the batteries.

Cheap PEM Fuel Cells Could Widely Displace Thermal Power Stations

The possibility that hypercars' low power requirements could permit the early adoption of PEMFCs is important for the electric utility industry, because cheap PEMFCs fueled with natural gas should be able to undercut the *short*-run marginal cost of generating power from even the most efficient thermal power stations. For example, the net electrical output efficiency of a PEMFC using reformed methane is often quoted at ~40–50% (LHV) 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, but with both, the best technology is now typically >50% and often in the high 50s. Natural gas at $3.7/GJ or $4/$10^3$ ft^3 (the average U.S. price to CNG fleet-vehicle refueling stations in 1992–93) would thus produce electricity at 3.0¢/kWh: 2.7¢/kWh for the fuel plus 0.3¢/kWh for the cost of a relatively expensive early fuel cell at ~$200/kW.[12] Note that this is the *delivered* electricity price, not busbar: it avoids all grid costs and losses, making three-cent power easily competitive with almost every utility's short-run marginal cost, even from the newest ~60%-efficient, but centrally located, combined-cycle gas turbines. In effect, the PEMFC is about as efficient as those turbines, but far smaller and more modular, much easier to mass-produce, and probably cheaper per kW even at quite modest production volumes.

However, this comparison neglects one of the fuel cell's most valuable benefits: it continuously produces onsite not only electricity but also waste heat with a useful temperature of ~80°C, ideal for heating and cooling buildings or for heating domestic water. Such free waste heat is valuable, because it can displace heat otherwise produced from fuels like natural gas using furnaces or boilers that have their own costs and losses, both valuable to avoid. Each kWh (3.6 MJ) of fuel used by the PEMFC will yield at least 1.8 MJ of electricity *plus* up to 1.8 MJ of free waste heat, which when timely (needed approximately when produced) can displace 2.6 MJ of fuel normally used by a typical ~70%-efficient commercial boiler. The avoided boiler fuel is thus worth a fraction of the fuel cell's fuel cost (about 2.6/3.6), multiplied by the duty factor of the local heat requirements. For a typical commercial building requiring substantial

[12] Assuming, for illustration, a 10%/y real fixed charge rate and a 75% capacity factor, such as might be characteristic of an efficient building with fairly long occupied hours.

heating or cooling at virtually all times of the day and year, this waste-heat credit (plus an estimated 3% allowance for displacing the capital and maintenance costs of the boiler) would offset three-fourths of the fuel cell's natural-gas costs, reducing the effective net cost of the electricity to only 1.0¢/kWh. That beats the fuel, operation, maintenance, and major-repair costs of a typical gas-fired, coal, or nuclear power plant—even at the busbar, without its grid costs for delivery to the customer—by a factor of about two to five.

To be sure, the actual site-specific comparison is far more complex, because persistent temporal imbalances—the less efficient the buildings, probably the greater the imbalances—are likely between the supply of and the demand for both heat and electricity. But real-time electricity pricing, the relative ease of storing heat, and the prospect that cheap superflywheel or ultracapacitor electrical storage will enter the market in the late 1990s (also stimulated by the vehicular market) all suggest that these details will not materially change the conclusion: cheap PEMFCs could economically and practically displace any thermal power station in circumstances that occur very widely—wherever there is natural gas and a moderately frequent market (even as small as kilowatt scale) for the waste heat.

This prospect of putting essentially all thermal power plants out of business is not purely academic. For example, the current U.S. private fleet of ~150 million cars, excluding other motor vehicles, and averaging 20 continuously rated kW of onboard fuel-cell APU capacity per vehicle, would represent a generating capacity about *five times that of all U.S. electric utilities.* The fuel cells could be run silently, very cleanly, and at essentially zero marginal capital cost (since they are already paid for and can run far longer than cars normally last) when plugged into both the electric and the natural-gas grids, assuming a simple reformer to produce hydrogen either onboard or at the plug-in site. The average American car is parked ~96% of the time, usually in habitual sites such as the home or workplace. Although the electric-and-gas connection would have a modest capital and metering cost, it would typically be in sites already served, or nearly served, by both grids, and the cost of the electric hookup would probably be less than the "distributed benefits" (Lovins and Yoon 1993) of onsite generation to support local electric distribution.

In these circumstances, one can reasonably expect entrepreneurs to start providing hookups. A simple credit-card swipe when plugging in the car would automatically handle the gas billing and electricity credit, both at real-time prices. These plus a profit for the entrepreneur could well repay a significant fraction of the depreciation and finance costs of owning the car—together accounting for ~64% of the total cost of the typical American family's second-biggest asset.[13] If even a modest fraction of car-owners chose to take advantage of this opportunity to earn significant profit from that otherwise idle asset, they could well displace much if not all fossil-fueled power generation most or all of the time. To utilities now expecting to *sell* a lot of their surplus electricity to battery-electric cars, and already concerned about stranded generating assets exposed to wholesale competition from combined-cycle gas turbines, such widespread competition from a potentially ubiquitous and flexible power source, already bought for other reasons, and owned by a large and potentially strong constituency, is hardly a welcome prospect.

In the long run, it is probably not important whether hypercars first pull PEMFCs into mass production, lowering their cost until they displace power plants, or instead the prospect of beating power plants (starting in niche markets with costly electricity or bottlenecked grids but cheap gas) inspires entrepreneurs to aggregate PEMFC markets for micro-scale combined-heat-and-power until the fuel cells become cheap enough to use in cars. Whatever the sequence, the point is that these two enormous markets will play off each other: *whichever happens first will ensure that the other quickly follows.* As in electrical storage, this greatly heightens the likelihood that both will happen. Both are very good news for issues like climatic change. Together, fuel-cell hypercars plus the resulting displacement of fossil-fueled power plants could reduce by more than 2-fold, perhaps close to 4-fold (with solar hydrogen or other renewable fuel), all present climate-threatening emissions of radiatively active gases from, say, the United States.

---

[13] 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 would often generate during peak hours, earning 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 MY1994 U.S. passenger car (AAMA 1994, p. 56).

REFERENCES

Allison Gas Turbine Division of General Motors 1993: *Research and Development of Proton-Exchange Membrane (PEM) Fuel Cell System for Transportation Applications: Initial Conceptual Design Report*, report EDR 16194 to Office of Transportation Technologies, U.S. Department of Energy, 30 November, at p. C-4.

James, B.D., G.N. Baum, and I.F. Kuhn, Jr. 1994: *Technology Development Goals for Automotive Fuel Cell Power Systems*, August final report ANL-94/44 to Argonne National Laboratory, Directed Technologies, Inc. (see Thomas and Kuhn, *op. cit. infra*).

Lovins, A.B. 1995: "Supercars:Advanced Ultralight Hybrid Vehicles,"*Wiley Encyclopedia of Energy Technology and the Environment*, John Wiley & Sons (New York)

Lovins, A.B. and D. Yoon 1993: "Renewables in Integrated Energy Systems," RMI Publication #E94-12.

Lovins *et al.* 1996: *Hypercars: Materials, Manufacturing, and Policy Implications.* Rocky Mountain Institute Publication.

Moore, T.C. & A.B. Lovins 1995: "Vehicle Design Strategies to Meet and Exceed PNGV Goals," SAE951906

Thomas, C.E. and I.F. Kuhn, Jr. 1995: *Electrolytic Hydrogen Production Infrastructure Options Evaluation*, March final technical report to National Renewable Energy Laboratory under Subcontract #ACF-4-14226-01, Directed Technologies, Inc. (4001 N. Fairfax Dr., Suite 775, Arlington, VA 22203).