STRATEGY FOR THE HYDROGEN TRANSITION

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Abstract: *A rapid and profitable commercialization path for fuel cells and H_2 can be executed by coordinating convergent trend 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 ultra light-hybrid vehicles whose inherently high efficiency permits their full-cell stacks to rely on conveniently compact onboard thanks 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 three generation 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 off-peak 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 hyper cars could adopt fuel cells at several fold higher prices, hence several years earlier, than conventional cars. The general-vehicle market could then be opened to hydrogen by first using the spare off-peak capacity of buildings, H_2 sources to serve vehicles too-particularly vehicles whose drives work or live in or near the sane 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. Wiliams'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.

Keywords: *hydrogen, fuel-cell , strategy, reforming*

1. 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 widesesspread[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 procesors[2] fueled by gasoline, mathanol[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 propolsion[4]. The case for methanol 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 feedstock.

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

- That the vehicles must be inefficient-essentionally 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.

2. 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-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) several –fold lighter-weight and lower-drag than conventional versions. This requires a highly integrated ultra light design synergies, mechanical simplification, and open-architecture whole –platform software and electronics. 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 folds, so that:

- Several fold less fuel-cell capacity is required: cca25-30 kW_e for 4-passenger sedan or cca30-50 kW for a 5-6 passenger sedan or larger light-duty vehicle,

- This reduced capacity makes a fuel-cell price on the order of $100/kW$_e$ competitive-a several-fold 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 several fold lower price normally posited
- 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, pack gable bulk, and very low mass,
- 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 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 1999, such advantages for both customers and manufacturers had led billions of dollars 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 trade market term "Hypercar™") have already appeared in concept cars and market platforms in the late 1990s. Widespread market introduction and rapid spread of a wide range of vehicles incorporating the essential elements of that ultra light-hybrid design synthesis, including fuel-cell versions, appear inevitable soon after the turn of the century.

Of course, a Hyper car could make its traction power onboard from any liquid fuel, including gasoline, methanol, or biofuels, using an engine or turbine-driven generation. It would simply not be as clean or efficient as a direct-hydrogen fuel-cell version. In round numbers, an engine-driven, liquid-fueled hyper car would normally achieve about 2-3 L/100 km, while a hydrogen-fuel-cell version would achieve roughly 2 or fewer L/100 (both expressed as liters of gasoline-equivalent). Since the Hyper car relaxes the fuel-cell-cost and tank-packaging constraints that make direct hydrogen fueling unattractive in conventional fuel-cell-powered cars, 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.

3. DEPLOYMENT OF FUEL CELL IN BUILDINGS AND VEHICLES

To be competitively used in light-duty vehicles, even in hyper cars, 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 stress 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 cell will behave in the same way. 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 several fold 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 several fold cheaper than just the wires to deliver that station's power to a building, where the fuel cell could already be.

When fuel cell 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, which is a about a fifth to a tent the cost of today's cheapest combined-cycle gas-fired power stations. Most automakers assume they need such low cost before fuel cells can complete with internal-combustion engines. As described earlier, however, Hyper cars need several fold 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 hyper cars a few years' head start in adopting fuel cells an important market advantage for both hyper cars and fuel cells.

However, exclusive focus on cars leads to the incorrect conclusion that fuel-cell costs must be driven down to automotive acceptable levels by brute-force, loss-leader scale up of production for cars. It is more plausible that the initial markets that build production volume and cut cost will instead 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 turn 50 or more percent of the hydrogen's energy into highly reliable, premium-quality electricity, and the reminder into 70^0C pure water ideal for heating, cooling and dehumidifying buildings using a modular "balance-of-system" black box witch several capable firms are already developing. In a typical building, such services would help pay for natural gas and a fuel processor. With the fuel expenses thus largely covered, electricity from early production fuel cells should be cheap enough 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. 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.

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 $15MW_e$ 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 cell's cca70^0C 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 chip making 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, 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 Hyper cars.

However, once fuel cells become cost-effective for, and are installed in, a Hyper car, it becomes more than just a car. It is also, in effect, a clean, silent, ultra reliable power station on wheels, with a generating capacity of at least 20 kilowatts.

Perhaps surprisingly, the key 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 cell's 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 evolution of infrastructure for hydrogen fueling.

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. The car's inventory of hydrogen would be modest and would typically be stored in an extremely strong carbonfiber 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 cant's burn you unless you're practically inside it, in contrast to burning gasoline and other hydrocarbons 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 buildings 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 thermo-chemical plant-into the car so it can convert liquid fuels (gasoline or methanol) into hydrogen onboard. Instead, a new hydrogen infrastructure could be built step, using established methods and markets that could each be profitable. How can this transition actually occur?

Producing hydrogen is a little-known but large and mature industry. 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 dozes of cars.

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 [full-cell] to provide adequate return on investment." It 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; 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.

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 Hyper cars or other vehicles, the more entrepreneurs will want to start installing street-corner "gas stations" 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.

4. CONCLUSION

This combination of technologies can thus ameliorate, at a profit, close to two-thirds of America's carbon- dioxide emissions 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, for 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, 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 hyper cars will ultimately save as much oil as OPEC now sells, making gasoline prices both low and less relevant. Between Hyper cars and other new ways to displace oil at lower coast in each of its main uses today, oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices. 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 ($\leq$2 L/100 km) cars as a matter of urgency. Early signs can already be see that dramatically more efficient vehicles will soon be entering the marketplace, but helping this 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; 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.

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