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The history of alternative transportation fuels is largely a history of failures. Niche fuels such as liquefied petroleum gases (LPG) and compressed natural gas (CNG) have persisted here and there over the years, but never captured significant market penetration for a sustained period. The two exceptions are ethanol in Brazil, made from sugar cane, and ethanol in the US, made from corn. For both these cases, the fuel was heavily subsidized and protected for decades. They are now commercially successful, though at relatively small volumes, and will remain so as long as oil prices remain high. The real lesson is that success came only after decades of durable policy and subsidies, high oil prices and, in the case of Brazil, a committed automotive industry (first building dedicated ethanol vehicles and then after their failure following a decade later with flexible fuel vehicles).

Will hydrogen succeed, where so many previous alternatives have failed? Will hydrogen be able to elicit durable policy support, as did ethanol in Brazil and the US? Might hydrogen succeed on a grand scale, where others have not?

Hydrogen clearly provides the potential for huge energy and environmental improvements. But skeptics abound, for many good reasons. Academics question near-term environmental benefits, and activists and environmental groups question the social, environmental, and political implications of hydrogen made from coal and nuclear. Some critics, notably Joseph Romm,[2] believe that a major effort to introduce hydrogen cars before 2030 would actually undermine efforts to reduce emissions of heat-trapping greenhouse gases such as CO_2. Others say we are picking the wrong horse. Paul MacCready argues in *Hydrogen Transitions*[3] that improved battery technology will trump hydrogen and fuel cell vehicles. Advocates of plug-in hybrid vehicles and biofuels see these as nearer-term and easier to implement. And many, including John DeCicco of Environmental Defense, also in *Hydrogen Transitions,*[4] argue that the hydrogen transition is premature at best. As the 2004 National Academies and IEA 2005 reports on hydrogen[5] assert, there are indeed many questions to answer and many barriers to overcome before hydrogen's potential can be realized.

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[1] This paper is updated from Sperling and Ogden, The Hope for Hydrogen, *Issues in Science and Technology*, Spring 2004, pp. 82-86
[2] Joe Romm, *The Hype about Hydrogen*, Island Press, 2004.
[3] Chapter 16 in Sperling, D. and James Cannon, eds, *The Hydrogen Energy Transition*, Elsevier Press, 2004.
[4] Chapter 17, ibid.
[5] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,* National Academy Press, Washington, DC, 2004 www.nap.edu/books/0309091632/html

What is remarkable in the early stages of this debate is the source of public opposition: it is not coming from car or oil companies. It is coming primarily from those most concerned about environmental and energy threats. The hydrogen debate in the US has been sucked into the larger debate over President Bush's environmental record. The environmental community fears that the promise of hydrogen is being used to camouflage eviscerated and stalled regulations, and that it will crowd out R&D for deserving near term energy efficiency and renewable opportunities. What the administration and others portray as a progressive, long-term strategy, others see as bait and switch. Indeed, a backlash has developed against what many see as hydrogen hype.

Perhaps that story is correct. Perhaps it is true that without hydrogen, government leaders would pursue more aggressive fuel economy standards and larger investments in renewable energy. We remain skeptical. Even if true in Washington, DC, is it also true in Sacramento, Brussels, and Tokyo? Moreover, there is the larger question of the size of the public R&D energy pie. If energy efficiency and climate change are important public issues, then quibbling over tens of millions of dollars in the DOE budget is missing the point. It should not be seen as a zero sum game. Energy R&D in the US, both public and private, is much lower than it was 25 years ago. It needs to increase dramatically to provide a foundation for the 21st century clean energy challenges. Compelling initiatives lead to larger budgets.

In any case, this paper tells a different story. The first point is that hydrogen is a long-term strategy, and that any coherent energy strategy should have a long-term component. Second, hydrogen policies are synergistic with near-term policies aimed at energy efficiency, greenhouse gas reduction, and enhanced renewable investments. Hydrogen vehicles will not happen without those policies in place. Indeed, hybrid vehicles are an essential step on the technological transition to fuel cells and hydrogen. And third, if not hydrogen, then what? No other long-term option, with the possible exception of battery-powered electric vehicles, approaches the breadth and magnitude of hydrogen's public good benefits.

What History Tells Us

All previous alternative transportation fuels ultimately failed in passenger vehicle markets, largely for two reasons: they provided no private benefits and claims of large public benefits regarding pollution and energy security proved to be overstated. The private benefits from compressed natural gas, ethanol, methanol, propane, and early battery electric vehicles were nil. All have shorter distances between refueling, since these fuel options all have lower energy density than gasoline, and have different safety and performance attributes, often perceived as inferior. The only clear benefits are emissions and energy security -- but few consumers purchase a vehicle for public-good reasons. Overstated claims for new fuels were not intentionally deceptive. Rather, they reflected a poor understanding of energy and environmental innovation and policy. Two errors stand out: understated forecasts of oil supply and gasoline quality, and overstated environmental and economic benefits of alternative fuels versus improved conventional fuels and vehicles. Oil turned out to be cheap and abundant, thanks to improved technologies for finding and extracting oil, gasoline and diesel fuel were reformulated to be cleaner, and internal combustion engines are now nearly zero-emitting.

What do these lessons imply for hydrogen? First, hydrogen is unlikely to succeed on the basis of environmental and energy advantages alone—at least in the near to medium term (unless oil prices were to remain at 2006 levels of $70 per barrel for many years). Hydrogen will find it difficult to compete with the century-long investment in petroleum fuels and internal combustion engines. Hybrid-electric vehicles, cleaner combustion engines, and cleaner fuels will provide almost as much energy and environmental benefit on a per vehicle basis for some time. (Though, hydrogen would provide modest benefits even if made from natural gas, as is likely in the near-term: our careful reviews of the GREET model, MIT's 2003 study[6], and the most recent efficiency data from Honda, suggests that well-to-wheels carbon emissions from a hydrogen fuel cell vehicle will be about 10-40% less than for full gasoline hybrids such as a Prius, with oil consumption and tailpipe pollutant emissions reduced even further.) Over the next decade or so, advanced gasoline and diesel vehicles will be more widespread and thus deliver more benefits sooner than hydrogen and fuel cells ever could. Hydrogen is neither the easiest nor the cheapest way to gain large near- and medium-term air pollution, greenhouse gas, or oil reduction benefits.

These incremental enhancements are far from exhausted, but there is almost no hope that oil or carbon dioxide reductions could offset projected vehicle usage increases – even if the entire fleet of vehicles were converted to hybrid-electric and diesel power -- never mind achieve the radical de-carbonization and oil reductions likely to be needed later this century.

The Case for Hydrogen

The case for hydrogen is threefold. First, hydrogen fuel cell vehicles appear to be a superior consumer product desired by the automotive industry. Second, as indicated by the National Academies study, the potential exists for dramatic reductions in the cost of hydrogen production, distribution, and use. And third, hydrogen provides the potential for zero tailpipe pollution, near-zero well to wheels emissions of greenhouse gases, and diversification away from oil, simultaneously addressing the most vexing challenges facing the fuels sector, beyond what could be achieved with hybrid vehicles and energy efficiency.

The case for hydrogen is supported by the automotive industry's embrace of fuel cells. The automotive industry, or at least an important slice of it, sees fuel cells as its inevitable and desired future. This was not true for any previous alternative fuel or vehicle technology. The 2004 National Academies report highlights the attractions of fuel cell vehicles. It notes that not only are fuel cells superior environmentally, but they also provide extra value to customers. They have the potential to provide most of the benefits of battery-electric vehicles without the short range and long recharge time. They offer quiet operation, rapid acceleration from a standstill due to the torque characteristics of

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[6] M.A. Weiss, J.B. Heywood, A. Schafer, and V.K. Natarajan, *Comparative Assessment of Fuel Cell Cars*, LFEE Publications, MIT, Cambridge, MA, 2003.

electric motors, and potentially low maintenance requirements. They can provide remote electrical power—for construction sites and recreational uses, for example—and even act as distributed electricity generators when parked at homes and offices. Importantly, they also provide additional attractions to automakers. By eliminating most mechanical and hydraulic subsystems, they provide greater design flexibility and the potential for using fewer vehicle platforms, which allow more efficient manufacturing approaches. Fuel cells are a logical extension of the technological pathway automakers are already following and would allow a superior consumer product—if fuel cell costs become competitive and if hydrogen fuel can be made widely available at reasonable cost.

Those two ifs remain unresolved and are central to the hydrogen debate. Fuel cell costs are on a steep downward slope and are now perhaps only a factor of four too high (based on a recent US Department of Energy study that suggests mass production of today's state-of-the-art fuel cell stack would cost about $125 per kilowatt[7]), though huge amounts of engineering are still needed to improve manufacturability, ensure long life and reliability, and enable operation at extreme temperatures. It appears that a handful of automotive companies are continuing to make those engineering investments and seem convinced that they are on track to achieve the necessary cost reductions and performance enhancements.

The second *if* is hydrogen availability, which is perhaps the greatest challenge of all. The problem is not production cost or sufficient resources. Hydrogen is already produced from natural gas and petroleum at costs similar to gasoline. With continuing R&D investment, the cost of producing hydrogen from a variety of abundant fossil and renewable sources should prove to be not much greater than producing gasoline, according to the National Academies' study.

The key supply challenges are as follows. First is the need for flexibility. There are many possible paths for making and delivering hydrogen, and it is difficult at this time to know which will prevail. A hydrogen economy might look quite different in different regions, depending on local resources. Second, because private investment will naturally gravitate toward conventional fossil energy sources, currently the lowest cost way to make hydrogen, government needs to accelerate R&D of zero-emission hydrogen production methods. Renewable hydrogen production is a key area for focused R&D. . Carbon dioxide (CO_2) sequestration—a prerequisite if abundant coal in the United States, China, and elsewhere is to be used—is another possible path to very low emission hydrogen. Although the cost of capturing carbon from large fossil plants and sequestering it is not a showstopper in a large range of locations and situations, CO_2 sequestration faces uncertain public acceptance. Will CO_2 be viewed like nuclear waste, leading to permitting delays and extra costs? Clearly, hydrogen will benefit from development of renewables and CO_2 sequestration technologies ongoing in the electric sector.

The third supply-related challenge is logistical in nature. How can hydrogen be provided at local refueling sites, offering both convenience and acceptable cost to consumers

[7] National Research Council, *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report*, National Academies Press, Washington, DC, 2005, Table 3-2.

during a transition? Today's existing natural gas and petroleum distribution systems are not necessarily good models for future hydrogen distribution, especially in the early stages of hydrogen use when consumption is small and dispersed. If future hydrogen systems attempt to simply mimic today's energy systems from the beginning, distribution costs could be untenably large, and the hydrogen economy will be stillborn. Unlike for liquid transportation fuels, hydrogen storage, delivery and refueling are major contributors to delivered costs. Even for major fossil-based hydrogen production facilities under study, distribution and delivery costs are estimated to be equal to the costs of production.

Clearly, a creative, evolutionary approach is needed, eventually leading to a system that serves both stationary and mobile users, relies on small as well as large hydrogen production facilities, accesses a wide variety of energy feedstocks, incorporates carbon dioxide capture and sequestration, and is geographically diverse. In the very early stages of a transition, hydrogen might be delivered by truck from a central plant serving chemical uses as well as vehicles, or produced at refueling sites from natural gas or electricity. Distributed generation will be a key part of the solution, with production near or at the end-use site. The National Academies' report argues that the hydrogen economy will initially and perhaps for a very long time be based on distributed generation of hydrogen. Honda and General Motors propose placing small hydrogen refueling appliances at residences. Other innovative solutions would be needed, especially during the early phases. In cities with dense populations, pipelines would probably become the lowest cost delivery option, once a sizeable fraction of vehicles run on hydrogen. The transportation fuel and electricity and chemical industries might become more closely coupled, as the economics can sometimes be improved by co-production of electricity, hydrogen and chemical products. Transitions would proceed in different ways depending on the regional resources, and geographic factors. .

No Natural Enemies and One Important Friend

While the challenges are daunting, perhaps the most important insight is the absence of natural political or economic enemies. For starters, hydrogen is highly inclusive, capable of being made from virtually any energy feedstock, including coal, nuclear, natural gas, biomass, wind, and solar.

The oil industry is key. They effectively opposed battery electric vehicles because they saw no business case for themselves. Hydrogen is different. Oil companies are in actuality massive energy companies. They are prepared to supply any liquid or gaseous fuel consumers might desire, though of course they prefer a slow transition that allows them to protect sunk investments. Some, for instance, prefer that initial fuel cell vehicles carry reformers to convert gasoline into hydrogen. But by 2003, almost all major car companies became focused strictly on delivered hydrogen.

Oil companies will not allow the hydrogen economy to develop without them. Indeed, some have played key roles in promoting hydrogen, and many are active participants in hydrogen refueling demonstration projects around the world. But oil companies would not realize a rapid payoff from being first to market. Rather, they anticipate large financial losses that would be stanched only when hydrogen use became widespread. Without government support during the low volume transition stage, oil companies are unlikely to be early investors in the construction of hydrogen fuel stations. They are best characterized as watchful, strategically positioning themselves to play a large role if and when hydrogen "takes off".

Automakers see a different business reality. They see benefits from being first to market. They see hydrogen fuel cells as the desirable next step in the technological evolution of vehicles. Hydrogen's future appears to be tightly linked to automaker commitments to move fuel cells from the lab to the marketplace. The key question is whether and when they will ratchet up current investments of perhaps $200 million per year (in the case of the more aggressive automakers) to the much larger sums needed to tool factories and launch commercial products. Without automaker leadership, the transition will be slow, building on small entrepreneurial investments in niche opportunities, such as fuel cells in off-road industrial equipment, hydrogen blends in natural gas buses, innovative low-cost delivery of hydrogen to small users, and small energy stations simultaneously powering remote buildings and vehicle fleets.

If Not Hydrogen, Then What?

What are the alternatives to hydrogen? The only other serious long-term alternatives for fueling the transport sector are grid-supplied electricity and biomass. Indeed, we expect that all three options – hydrogen, electricity, and biofuels – will play important roles in powering our vehicles of the future.

Electricity is quite appealing on environmental and energy grounds. It allows for many of the same benefits as hydrogen – accessing renewable and other feedstocks and zero vehicular emissions. But every major automaker has abandoned its battery electric vehicle program, except for DaimlerChrysler's small factory in North Dakota producing the GEM neighborhood vehicle. Plug-in hybrids, which have been receiving considerable political and media interest in the US in the past year, provide a possible bridge and complement to pure battery electric vehicles. But for either plug-in hybrids or battery electric vehicles to be viable, several-fold improvements in batteries or other electricity storage devices would be required -- or massive investments would be needed in "third rail" electricity infrastructure that would incur substantial added cost for vehicles. Battery technology will continue to improve. But after a century of intense research, there still remains no compelling proposal that might reduce material costs sufficiently to render batteries competitive with internal combustion engines. Battery electric vehicles and plug-in hybrids will undoubtedly play an important future role, but whether they will evolve beyond niche applications remains unknown.

The other long-term proposal is biomass. Cellulosic materials, including trees and grasses, can be grown on the vast land areas of the US and elsewhere and converted into ethanol or methanol fuel for use in combustion engines (or fuel cells). While this energy option is renewable, the environmental effects of intensive farming are not trivial, and the land areas involved are massive. Cellulosic ethanol production technologies are not commercial today, though many remain hopeful they might be by 2015. Moreover, there are few regions in the world available for extensive energy farming, and thus transferability opportunities are limited (unlike the case with hydrogen and electric technologies).

Still another long term option is fossil-based synfuels, whereby shale oil, tar sands, and coal are converted into petroleum-like fuels, and then burned in combustion engines, or converted into hydrogen at fuel stations or on-board vehicles for use in fuel cells. But with all these options, carbon capture at the site is more difficult than with coal-to-hydrogen options, CO_2 volumes would be massive, and the overall energy efficiency would be far inferior. The CO_2 emissions of gasoline made from Canadian tar sands, for instance, are about 50% greater on a lifecycle basis than gasoline made from conventional gasoline.

We conclude that hydrogen merits strong support, if only for the absence of a more compelling long-term option.

Hydrogen's Precarious Future

The transition to a hydrogen economy will not be easy nor straightforward. Like all alternative fuels past and present, it faces daunting challenges. But hydrogen *is* different. It accesses a broad array of energy resources, potentially provides broader and deeper societal benefits than any other option, potentially provides large private benefits, has no natural political or economic enemies, and it has a strong industrial proponent in the automotive industry.

In the end, though, the hydrogen situation is precarious. Beyond a few car companies and a scattering of entrepreneurs, academics, and environmental advocates, support for hydrogen is thin. While many rail against the hydrogen hype, the greater concern perhaps should be the fragile support for hydrogen. Politics aside, we applaud the United States, California, Canada, and others for starting down a path toward a sustainable future. Although we do not know when or even if the hydrogen economy will eventually dominate, we do believe that starting down this path is good strategy.

The key is enhanced science and technology investments, both public and private, and a policy environment that encourages those investments. Fuel cells and hydrogen provide a good marker to use in formulating policy and gaining public support. Of course, policy should remain focused on near-term opportunities. But good near-term policy, such as improving fuel economy, is also good long-term policy. It sends signals to businesses and customers that guide them toward investments and market decisions that are beneficial to society, not only in the near term but also the long term. It appears to us that hydrogen is a highly promising option that we should nurture as part of a broader science, technology, and policy initiative. The question is how, not if.