TESTIMONY

For the Hearing

Reviewing the Hydrogen Fuel and FreedomCAR Initiatives

SUBMITTED
TO
THE HOUSE SCIENCE COMMITTEE

BY

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Mr. Chairman and esteemed members of the Science Committee, I thank you for the opportunity to submit this testimony. I wish to express my appreciation for the strong support this committee has shown for clean energy technology R&D over the course of several decades.

Hydrogen and fuel cell cars are being hyped today as few technologies have ever been. In his January 2003 State of the Union address, President Bush announced a $1.2 billion research initiative, "so that the first car driven by a child born today could be powered by hydrogen, and pollution-free." The April 2003 issue of *Wired* magazine proclaimed, "How Hydrogen can save America." In August 2003, General Motors said that the promise of hydrogen cars justified delaying fuel-efficiency regulations.

Yet, for all the hype, a number of recent studies raise serious doubts about the prospects for hydrogen cars. In February 2004, a prestigious National Academy of Sciences panel concluded, "In the best-case scenario, the transition to a hydrogen economy would take many decades, and any reductions in oil imports and carbon dioxide emissions are likely to be minor during the next 25 years." And that's the best case. Realistically, as I discuss in my new book *"The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate,"* a major effort to introduce hydrogen cars before 2030 would undermine efforts to reduce emissions of heat-trapping greenhouse gases like carbon dioxide—the main culprit in last century's planet-wide warming of 1 degree Fahrenheit.

As someone who helped oversee the Department of Energy's program for clean energy, including hydrogen, for much of the 1990s—during which time we increased hydrogen funding by a factor of ten with the support of the Committee—I believe that continued research into hydrogen remains important because of its potential to provide a pollution-free substitute for oil in the second half of this century. But if we fail to limit greenhouse gas emissions over the next decade—and especially if we fail to do so because we have bought into the hype about hydrogen's near-term prospects—we will be making an unforgivable national blunder that may lock in global warming for the U.S. of 1 degree Fahrenheit *per decade* by mid-century.

HYDROGEN and FUEL CELLS

Hydrogen is not a readily accessible energy source like coal or wind. It is bound up tightly in molecules like water and natural gas, so it is expensive and energy-intensive to extract and purify. A hydrogen economy—which describes a time when the economy's primary energy carrier is hydrogen made from sources of energy that have no net emissions of greenhouse gases—rests on two pillars: a pollution-free source for the hydrogen itself and a fuel cell for efficiently converting it into useful energy without generating pollution.

Fuel cells are small, modular, electrochemical devices, similar to batteries, but which can be continuously fueled. For most purposes, you can think of a fuel cell as a "black box" that takes in hydrogen and oxygen and puts out only water plus electricity and heat.

The most promising fuel cell for transportation is the Proton Exchange Membrane (PEM) fuel cell, first developed in the early 1960s by General Electric for the Gemini space program. The price goal for transportation fuel cells is to come close to that of an internal combustion engine, roughly $30 per kilowatt. Current PEM costs are about 100 times greater. It has taken wind power and solar power each about twenty years to see a tenfold decline in prices, after major government and private-sector investments in R&D, and they still each comprise well under 1% of US electricity generation. A major technology breakthrough is needed in transportation fuel cells before they will be practical.

THE STORAGE SHOW-STOPPER?

Running a fuel cell car on pure hydrogen, the option now being pursued most automakers and fuel cell companies, means the car must be able to safely, compactly, and cost-effectively store hydrogen onboard. This is a major technical challenge. At room temperature and pressure, hydrogen takes up some 3,000 times more space than gasoline containing an equivalent amount of energy. The Department of Energy's 2003 *Fuel Cell Report to Congress* notes:

> Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles and fit in an envelope that does not compromise either passenger space or storage space. Current energy storage technologies are insufficient to gain market acceptance because they do not meet these criteria.

The most mature storage options are liquefied hydrogen and compressed hydrogen gas.

Liquid hydrogen is widely used today for storing and transporting hydrogen. Liquids enjoy considerable advantages over gases from a storage and fueling perspective: They have high energy density, are easier to transport, and are typically easier to handle. Hydrogen, however, is not typical. It becomes a liquid only at -423 °F, just a few degrees above absolute zero. It can be stored only in a super-insulated cryogenic tank.

Liquid hydrogen is exceedingly unlikely to be a major part of a hydrogen economy because of the cost and logistical problems in handling liquid hydrogen and because liquefaction is so energy intensive. Some 40% of the energy of the hydrogen is required to liquefy it for storage. Liquefying one kg of hydrogen using electricity from the U.S. grid would by itself release some 18 to 21 pounds of carbon dioxide into the atmosphere, roughly equal to the carbon dioxide emitted by burning one gallon of gasoline.

Compressed hydrogen storage is used by nearly all prototype hydrogen vehicles today. Hydrogen is compressed up to pressures of 5,000 pounds per square inch (psi) or even 10,000 psi in a multistage process that requires energy input equal to 10% to 15% of the hydrogen's usable energy content. For comparison, atmospheric pressure is about 15 psi.

Working at such high pressures creates overall system complexity and requires materials and components that are sophisticated and costly. And even a 10,000-psi tank would take up 7 to 8 times the volume of an equivalent-energy gasoline tank or perhaps four times the volume for a comparable range (since the fuel cell vehicle will be more fuel efficient than current cars).

The National Academy study concluded that both liquid and compressed storage have "little promise of long-term practicality for light-duty vehicles" and recommended that DOE halt research in both areas. Practical hydrogen storage requires a major technology breakthrough, most likely in solid-state hydrogen storage.

AN UNUSUALLY DANGEROUS FUEL

Hydrogen has some safety advantages over liquid fuels like gasoline. When a gasoline tank leaks or bursts, the gasoline can pool, creating a risk that any spark would start a fire, or it can splatter, posing a great risk of spreading an existing fire. Hydrogen, however, will escape quickly into the atmosphere as a very diffuse gas. Also, hydrogen gas is non-toxic.

Yet, hydrogen has its own major safety issues. It is highly flammable with an ignition energy 20 times smaller than that of natural gas or gasoline. It can be ignited by cell phones and electrical storms located miles away. Hence, leaks pose a significant fire hazard. At the same time, it is one of the most leak-prone of gases. Odorants like sulfur are impractical, in part because they poison fuel cells. Hydrogen burns nearly invisibly, and people have unwittingly stepped into hydrogen flames. Hydrogen can cause many metals, including the carbon steel widely used in gas pipelines, to become brittle. In addition, any high-pressure storage tank presents a risk of rupture. For these reasons, hydrogen is subject to strict and cumbersome codes and standards, especially when used in an enclosed space where a leak might create a growing gas bubble.

Some 22% or more of hydrogen accidents are caused by undetected hydrogen leaks. This "despite the special training, standard operating procedures, protective clothing, electronic flame gas detectors provided to the limited number of hydrogen workers," as Russell Moy, former group leader for energy storage programs at Ford Motors has wrote in the November 2003 *Energy Law Journal*. Moy concludes "with this track record, it is difficult to imagine how hydrogen risks can be managed acceptably by the general public when wide-scale deployment of the safety precautions would be costly and public compliance impossible to ensure." Thus, major innovations in safety will be required before a hydrogen economy is practical.

AN EXPENSIVE FUEL

A key problem with the hydrogen economy is that pollution-free sources of hydrogen are unlikely to be practical and affordable for decades. Indeed, even the pollution-generating means of making hydrogen are currently too expensive and too inefficient to substitute for oil.

Natural gas (methane or CH_4) is the source of 95% of U.S. hydrogen. The overall energy efficiency of the steam methane reforming process (the ratio of the energy in the hydrogen output to the energy in the natural gas fuel input) is about 70%.

According to a comprehensive 2002 analysis for the National Renewable Energy Laboratory by Dale Simbeck and Elaine Chang, the cost of producing and delivering hydrogen from natural gas, or producing hydrogen on-site at a local filling station, is $4 to $5 per kilogram (without adding in any fuel taxes), comparable to a price of gasoline of $4-$5 a gallon (since a kilogram of hydrogen contains about the same usable energy as a gallon of gasoline). This is over three times the current untaxed price of gasoline. Considerable R&D is being focused on efforts to reduce the cost of producing hydrogen from natural gas, but fueling a significant fraction of U.S. cars with hydrogen made from natural gas makes little sense, either economically or environmentally, as discussed below.

Water can be electrolyzed into hydrogen and oxygen. This process is extremely energy-intensive. Typical commercial electrolysis units require about 50 kiloWatt-hours (kWh) per kilogram, an energy efficiency of 70%. The cost today of producing and delivering hydrogen from a central electrolysis plant is estimated at $7 to $9 per kilogram. The cost of on-site production at a local filling station is estimated at $12 per kg. Replacing one half of U.S. ground transportation fuels in 2025 (mostly gasoline) with hydrogen from electrolysis would require about *as much electricity as is sold in the U.S. today*.

From the perspective of global warming, electrolysis makes little sense for the foreseeable future. Burning a gallon of gasoline releases about 20 pounds of carbon dioxide. Producing 1 kg of hydrogen by electrolysis would generate, on average, 70 pounds of carbon dioxide. Hydrogen could be generated from renewable electricity, but that would be even more expensive and, as we will see, renewable electricity has better uses for the next few decades.

Other greenhouse-gas-free means of producing hydrogen are being pursued. The Department of Energy's FutureGen project is aimed at designing, building, and constructing a 270-megawatt prototype coal plant that would cogenerate electricity and hydrogen while removing 90% of the carbon dioxide. The goal is to validate the viability of the system by 2020. If a permanent storage location can be found for the carbon dioxide, such as an underground reservoir, this would mean that coal could be a virtually carbon-free source of hydrogen. The Department is also pursuing thermochemical hydrogen production systems using nuclear power with the goal of demonstrating commercial scale production by 2015. Biomass (plant matter) can be gasified and converted into hydrogen in a process similar to coal gasification. The cost of delivered hydrogen from gasification of biomass has been estimated at $5 to $6.30 per kg. It is unlikely that any of these approaches could provide large-scale sources of hydrogen at competitive prices until after 2030.

Stranded investment is one of the greatest risks faced by near-term hydrogen production technologies. For instance, if over the next two decades we built a hydrogen infrastructure around small methane reformers in local fueling stations, and then decided that U.S. greenhouse gas emissions must be dramatically reduced, we would have to replace that infrastructure almost entirely. John Heywood, director of the Sloan Automotive Lab at the Massachusetts Institute of Technology, argues, “If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically.” A major technology breakthrough will be needed to deliver low-cost, zero-carbon hydrogen.

THE CHICKEN-AND-EGG PROBLEM

Bernard Bulkin, Chief Scientist for British Petroleum, discussed BP’s experience with its customers at the National Hydrogen Association annual conference in March 2003. He said, “if hydrogen is going to make it in the mass market as a transport fuel, it has to be available in 30 to 50% of the retail network from the day the first mass manufactured cars hit the showrooms.” Yet, a 2002 analysis by Argonne National Laboratory found that even with improved technology, “the hydrogen delivery infrastructure to serve 40% of the light duty fleet is likely to cost over $500 billion.” Major breakthroughs in both hydrogen production and delivery will be required to reduce that figure significantly.

Another key issue is the chicken-and-egg problem: Who will spend the hundreds of billions of dollars on a wholly new nationwide infrastructure to provide ready access to hydrogen for consumers with fuel-cell vehicles until millions of hydrogen vehicles are on the road? Yet who will manufacture and market such vehicles until the infrastructure is in place to fuel those vehicles? And will car companies and fuel providers be willing to take this chance before knowing whether the public will embrace these cars? I fervently hope to see an economically, environmentally, and politically plausible scenario for how this classic Catch-22 chasm can be bridged; it does not yet exist.

Centralized production of hydrogen is the ultimate goal. A pure hydrogen economy requires that hydrogen be generated from carbon-dioxide-free sources, which would almost certainly require centralized hydrogen production closer to giant wind-farms or at coal/biomass gasification power plants where carbon dioxide is extracted for permanent underground storage. That will require some way of delivering massive quantities of hydrogen to tens of thousands of local fueling stations.

Tanker trucks carrying liquefied hydrogen are commonly used to deliver hydrogen today, but make little sense in a hydrogen economy because of liquefaction’s high energy cost. Also, few automakers are pursuing onboard storage with liquid hydrogen. So after delivery, the fueling station would still have to use an energy-intensive pressurization system. This might mean that storage and transport alone would require some 50% of the energy in the hydrogen delivered, negating any potential energy and environmental benefits from hydrogen.

Pipelines are also used for delivering hydrogen today. Interstate pipelines are estimated to cost $1 million per mile or more. Yet, we have very little idea today what hydrogen-generation processes will win in the marketplace over the next few decades—or whether hydrogen will be able to successfully compete with future high-efficiency vehicles, perhaps running on other pollution-free fuels. This uncertainty makes it unlikely anyone would commit to spending tens of billions of dollars on hydrogen pipelines before there are very high hydrogen flow rates transported by other means, and before the winners and losers in both the production end and the vehicle end of the marketplace have been determined. In short, pipelines are unlikely to be the main hydrogen transport means until the post-2030 period.

Trailers carrying compressed hydrogen canisters are a flexible means of delivery, but are relatively expensive because hydrogen has such a low energy density. Even with technology advances, a 40-metric-ton truck might deliver only about 400 kg of hydrogen into onsite high-pressure storage. A 2003 study by ABB researchers found that for a delivery distance of 300 miles, the delivery energy approaches 40% of the usable energy in the hydrogen delivered. Without dramatic improvement in high-pressure storage systems, this approach seems impractical for large-scale hydrogen delivery.

Producing hydrogen on-site at local fueling stations is the strategy advocated by those who want to deploy hydrogen vehicles in the next two decades. On-site electrolysis is impractical for large-scale use because it would be highly expensive and inefficient, while generating large amounts of greenhouse gases and other pollutants. The hydrogen would need to be generated from small methane reformers. Although onsite methane reforming seems viable for limited demonstrations and pilots, it is also both impractical and unwise for large-scale application, for a number of reasons.

First, the upfront cost is very high—more than $600 billion just to provide hydrogen fuel for 40% of the cars on the road, according to Argonne. A reasonable cost estimate for the initial hydrogen infrastructure, derived from Royal Dutch/Shell figures, is $5000 per car.

Second, the cost of the delivered hydrogen itself in this option is also higher than for centralized production. Not only are the small reformers and compressors typically more expensive and less efficient than larger units, but they will likely pay a much higher price for the electricity and gas to run them. A 2002 analysis put the cost at $4.40 per kg (that is, equal to $4.40 per gallon of gasoline).

Third, "the risk of stranded investment is significant, since much of an initial compressed hydrogen station infrastructure could not be converted later if either a non-compression hydrogen storage method or liquid fuels such as a gasoline-ethanol combination proved superior" for fuel-cell vehicles." This was the conclusion of a major 2001 study for the California Fuel-Cell Partnership, a Sacramento-based public-private partnership to help commercialize fuel cells. Most of a methane-based investment would also likely be stranded once the ultimate transition to a pure hydrogen economy was made, since that would almost certainly rely on centralized production and not make use of small methane reformers. Moreover, it's possible the entire investment would be stranded in the scenario where hydrogen cars simply never achieve the combination of popularity, cost, and performance to triumph in the marketplace.

In the California analysis, it takes 10 years for investment in infrastructure to achieve a positive cash flow, and to achieve this result requires a variety of technology advances in both components and manufacturing. Also, even a small tax on hydrogen (to make up the revenue lost from gasoline taxes) appears to delay positive cash flow indefinitely. The high-risk and long-payback nature of this investment would seem far too great for the vast majority of investors, especially given alternative fuel vehicles history.

The U.S. has a great deal of relevant experience in the area of alternative fuel vehicles that is often ignored in discussions about hydrogen. The 1992 Energy Policy Act established the goal of having alternative fuels replace at least 10% of petroleum fuels in 2000, and at least 30% in 2010. By 1999, some one million alternative fuel vehicles were on the road, only about 0.4% of all vehicles. A 2000 General Accounting Office report explained the reasons for the lack of success:

> Fundamental economic impediments—such as *the relatively low price of gasoline, the lack of refueling stations for alternative fuels, and the additional cost to purchase these vehicles*—explain much of why both mandated fleets and the general public are disinclined to acquire alternative fuel vehicles and use alternative fuels.

It seems likely that all three of these problems will hinder hydrogen cars. Compared to other alternative fuels (such as ethanol and natural gas), the best analysis today suggests hydrogen will have a much higher price for the fuel, the fueling stations, and the vehicles.

The fourth reason that producing hydrogen on-site from natural gas at local fueling stations is impractical is that natural gas is simply the wrong fuel on which to build a hydrogen-based transportation system:

- The U.S. consumes nearly 23 trillion cubic feet (tcf) of natural gas today and is projected to consume more than 30 tcf in 2025. Replacing 40% of ground transportation fuels with hydrogen in 2025 would probably require an *additional* 10 tcf of gas (plus 300 *billion* kwh of electricity—10% of current power usage). Politically, given the firestorm over recent natural gas supply constraints and price spikes, it seems very unlikely the U.S. government and industry would commit to natural gas as a substitute for even a modest fraction of U.S. transportation energy.
- Much if not most incremental U.S. natural gas consumption for transportation would likely come from imported liquefied natural gas (LNG). LNG is dangerous to handle and LNG infrastructure is widely viewed as a likely terrorist target. Yet one of the major arguments in favor of alternative fuels has been their ability to address concerns over security and import dependence.
- Finally, natural gas has too much economic and environmental value to the electric utility, industrial, and buildings sectors to justify diverting significant quantities to the transportation sector, thereby increasing the price for all users. In fact, using natural gas to generate significant quantities of hydrogen for transportation would, for the foreseeable future, undermine efforts to combat global warming (as discussed below).

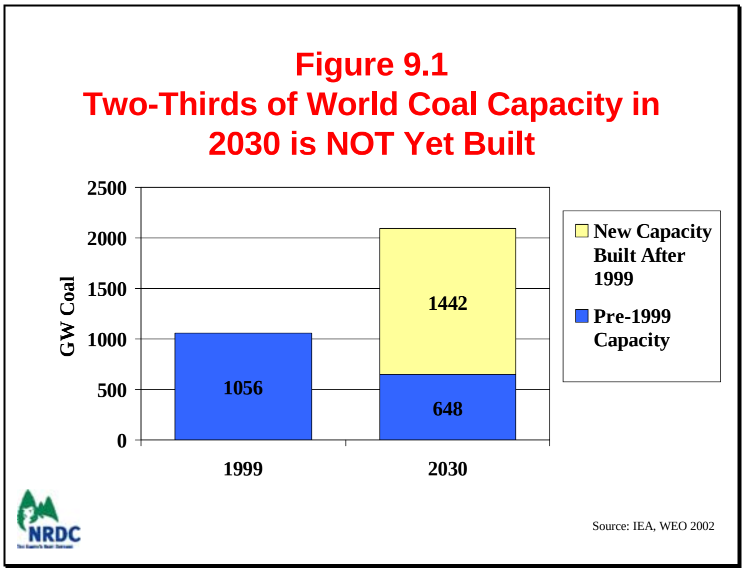
Thus, beyond limited pilot stations, it would be unwise to build thousands of local refueling stations based on steam methane reforming (or, for that matter, based on any technology not easily adaptable to delivery of greenhouse-gas-free hydrogen).

THE GLOBAL WARMING CENTURY

Perhaps the ultimate reason hydrogen cars are a post-2030 technology is the growing threat of global warming. Our energy choices are now inextricably tied to the fate of our global climate. The burning of fossil fuels—oil, gas and coal—emits carbon dioxide (CO_2) into the atmosphere where it builds up, blankets the earth and traps heat, accelerating global warming. We now have greater concentrations of CO_2 in the atmosphere than at any time in the past 420,000 years, and probably anytime in the past 3 million years—leading to rising global temperatures, more extreme weather events (including floods and droughts), sea level rise, the spread of tropical diseases, and the destruction of crucial habitats, such as coral reefs.

Carbon-emitting products and facilities have a very long lifetime: Cars last 13 to 15 years or more, coal plants can last 50 years. Also, carbon dioxide lingers in the atmosphere trapping heat for more than a century. These two facts together create an urgency to avoid constructing another massive and long-lived generation of energy infrastructure that will cause us to miss the window of opportunity for carbon-free energy until the next century.

Between 2000 and 2030, the International Energy Agency (IEA) projects that coal generation will double. The projected new plants would commit the planet to total carbon dioxide emissions of some 500 billion metric tons over their lifetime, which is roughly half the total emissions from all fossil fuel consumed worldwide during the past 250 years.



Building these coal plants would dramatically increase the chances of catastrophic climate change. What we need to build is carbon-free power. A March 2003 analysis in *Science* magazine by Ken Caldeira et al concluded that if our climate's sensitivity to greenhouse gas emissions is in the mid-range of current estimates, "stabilization at 4° C warming would require installation of 410 megawatts of carbon emissions-free energy capacity each day" for 50 years. Yet current projections for the next 30 years are that we will build just 80 megawatts per day.

Since planetary warming accelerates over time, and since temperatures over the continental US land mass are projected to rise faster than the average temperature of the planet, a warming of 4° C (over 7° F) means that by mid-century, the U.S. temperature could well be rising as much *per decade* as it rose all last century: one degree Fahrenheit. This scenario, which I am labeling "The Global Warming Century," would be a climate catastrophe—one that the American public is wholly unprepared for.

In February 2003, British Prime Minister endorsed the conclusion of Britain's Royal Commission on Environmental Pollution: "to stop further damage to the climate … a 60% reduction [in global emissions] by 2050 was essential."

Unfortunately, the path set by the current energy policy of the U.S. and developing world will dramatically *increase* emissions over the next few decades, which will force sharper and more painful reductions in the future when we finally do act. Global CO_2 emissions are projected to rise more than 50% by 2030. From 2001 to 2025, the U. S. Energy Information Administration (EIA) projects a

40% increase in U.S. coal consumption for electricity generation. And the U.S. transportation sector is projected to generate nearly half of the 40% rise in U.S. CO_2 emissions forecast for 2025, which again is long before hydrogen-powered cars could have a positive impact on greenhouse gas emissions

Two points are clear. First, we cannot wait for hydrogen cars to address global warming. Second, we should not pursue a strategy to reduce greenhouse gas emissions in the transportation sector that would undermine efforts to reduce greenhouse gas emissions in the electric generation sector. Yet that is precisely what a hydrogen-car strategy would do for the next few decades.

HYDROGEN CARS AND GLOBAL WARMING

For near-term deployment, hydrogen would almost certainly be produced from fossil fuels. Yet running a fuel-cell car on such hydrogen in 2020 would offer no significant life-cycle greenhouse gas advantage over the 2004 Prius running on gasoline.

Further, fuel cell vehicles are likely to be much more expensive than other vehicles, and their fuel is likely to be more expensive (and the infrastructure will probably cost hundreds of billions of dollars). While hybrids and clean diesels may cost more than current vehicles, at least when first introduced, their greater efficiency means that, unlike fuel cell vehicles, they will pay for most if not all of that extra upfront cost over the lifetime of the vehicle. A June 2003 analysis in *Science* magazine by David Keith and Alex Farrell put the cost of CO_2 avoided by fuel cells running on zero-carbon hydrogen at more than $250 per ton even with a very optimistic fuel cell cost. An advanced internal combustion engine could reduce CO_2 for far less and possibly for a net savings because of the reduced fuel bill.

Probably the biggest analytical mistake made in most hydrogen studies—including the recent National Academy report—is failing to consider whether the fuels that might be used to make hydrogen (such as natural gas or renewables) could be better used simply to make electricity. For example, the life-cycle or "well-to-wheels" efficiency of a hydrogen car running on gas-derived hydrogen is likely to be under 30% for the next two decades. The efficiency of gas-fired power plants is already 55% (and likely to be 60% or higher in 2020). Cogeneration of electricity and heat using natural gas is over 80% efficient. And by displacing coal, the natural gas would be displacing a fuel that has much higher carbon emissions per unit energy than gasoline. For these reasons, natural gas is far more cost-effectively used to reduce CO_2 emissions in electric generation than it is in transportation.

The same is true for renewable energy. A megawatt-hour of electricity from renewables like wind power, if used to manufacture hydrogen for use in a future fuel-cell vehicle, would save slightly under 500 pounds of carbon dioxide compared to the best *current* hybrids. That is less than the savings from using the same amount of renewable electricity to displace a future natural gas plant (800 pounds), and far less than the savings from displacing coal power (2200 pounds).

As the June 2003 *Science* analysis concluded: "Until CO_2 emissions from electricity generation are virtually eliminated, it will be far more cost-effective to use new CO_2-neutral electricity (such as wind) to reduce emissions by substituting for fossil-electric generation than to use the new electricity to make hydrogen." Barring a drastic change in U.S. energy policy, our electric grid will not be close to CO_2-free until well past 2030.

A 2004 analysis by Jae Edmonds et al. of Pacific Northwest National Laboratory concluded in that even "in the advanced technology case with a carbon constraint … hydrogen doesn't penetrate the transportation sector in a major way until *after 2035*."

CONCLUSION

Hydrogen and fuel-cell vehicles should be viewed as post-2030 technologies. In September 2003, a DOE panel on *Basic Research Needs for the Hydrogen Economy* concluded the gaps between current hydrogen technologies and what is required by the marketplace “cannot be bridged by incremental advances of the present state of the art,” but instead require "revolutionary conceptual breakthroughs.” In sum, “the only hope of narrowing the gap significantly is a comprehensive, long-range program of innovative, high risk/high payoff basic research.” The National Academy came to a similar conclusion.

The DOE should focus its hydrogen R&D budget on exploratory, breakthrough research. Given that there are few potential zero-carbon replacements for oil, the DOE is not spending too much on hydrogen R&D. But given our urgent need for reducing greenhouse gas emissions with clean energy, DOE *is* spending far too little on energy efficiency and renewable energy. If DOE’s overall clean energy budget is not increased, however, then it would be bad policy to continue shifting money away from efficiency and renewables toward hydrogen. Any incremental money given to DOE should probably be focused on deploying the cost-effective technologies we have today, to buy us more time for some of the breakthrough research to succeed.

The National Academy panel wrote that “it seems likely that, in the next 10 to 30 years, hydrogen produced in distributed rather than centralized facilities will dominate,” and so they recommended increased funding for improving small-scale natural gas reformers and water electrolysis systems. Yet any significant shift toward cars running on distributed hydrogen from natural gas or grid electrolysis would undermine efforts to fight global warming. DOE should not devote any R&D to these technologies. In hydrogen production, DOE should be focused solely on finding a low-cost, zero-carbon source, which will almost certainly be centralized. That probably means we won’t begin the hydrogen transition until after 2030 because of the logistical and cost problems associated with a massive hydrogen delivery infrastructure.

But we shouldn't be rushing to deploy hydrogen cars in the next two decades anyway, since not only are several R&D breakthroughs required, we also need a revolution in clean energy that dramatically accelerates the penetration rates of new CO_2-neutral electricity. Hydrogen cars might find limited value replacing diesel engines (for example in buses) in very polluted cities before 2030, but they are unlikely to achieve mass-market commercialization by then. That is why I conclude neither government policy nor business investment should be based on the belief that hydrogen cars will have meaningful commercial success in the near- or medium-term.

The longer we wait to deploy existing clean energy technologies, and the more inefficient, carbon-emitting infrastructure that we lock into place, the more expensive and the more onerous will be the burden on all segments of society when we finally do act. If we fail to act *now* to reduce greenhouse gas emissions—especially if fail to act because we have bought into the hype about hydrogen's near-term prospects—future generations will condemn us because *we* did not act when we had the facts to guide us, and *they* will most likely be living in a world with a much hotter and harsher climate than ours, one that has undergone an irreversible change for the worse.