THE PATH TO A HYDROGEN ECONOMY

HEARING

BEFORE THE

COMMITTEE ON SCIENCE
HOUSE OF REPRESENTATIVES

ONE HUNDRED EIGHTH CONGRESS

FIRST SESSION

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CONTENTS

March 5, 2003

Opening Statements

Witnesses

Appendix 1: Answers to Post-Hearing Questions

Appendix 2: Additional Material for the Record

THE PATH TO A HYDROGEN ECONOMY

WEDNESDAY, MARCH 5, 2003

House of Representatives,
Committee on Science,
Washington, DC.

The Committee met, pursuant to other business, at 10:30 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Sherwood L. Boehlert (Chairman of the Committee) presiding.

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

Hearing
On

The Path to a Hydrogen Economy

Wednesday, March 5, 2003
10:00 a.m. - 12:00 p.m.
2318 Rayburn House Office Building

WITNESS LIST

David Garman

Assistant Secretary for Energy Efficiency and Renewable Energy

U.S. Department of Energy

Alan C. Lloyd, Ph. D.

2003 Chairman

California Fuel Cell Partnership

Joan Ogden, Ph.D.

Research Scientist

Princeton Environmental Institute

Dr. Larry Burns

Vice President, Research, Development and Planning

General Motors

Don Huberts

Chief Executive Officer

Shell Hydrogen

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HEARING CHARTER

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

The Path to a Hydrogen Economy

WEDNESDAY, MARCH 5, 2003
10:00 A.M.–12:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Wednesday, March 5, 2003, at 10:00 a.m., the House Science Committee will hold a hearing on the President's Hydrogen Initiative, which is intended to lay the foundation for making the transition to an economy powered by hydrogen. If the widespread use of hydrogen is to become a reality, significant advances must be made, not only in vehicle technology, but also in hydrogen production and the infrastructure necessary to deliver it. The hearing will focus on the barriers to a hydrogen economy, and how the President's Initiative could address those barriers.

The hearing will focus on several overarching questions:

1) What are the greatest hurdles the country will face in converting to a hydrogen economy? To what extent is a federal effort needed to clear the way?
2) What specific and comprehensive goals are needed for the Hydrogen Initiative to ensure the fastest possible development and widespread utilization of hydrogen?
3) Will technology research alone lead to a transition to hydrogen, or will it be necessary to apply policy tools? How should a research and development effort take these policy choices into account?

Background

In his State of the Union speech, President Bush announced the creation of a new Hydrogen Initiative—a $1.2-billion, five-year research and development program to develop the technology and the hydrogen infrastructure for vehicles whose only emissions would be water vapor.

The Hydrogen Initiative would build on FreedomCAR, a $500 million research program announced last year by the Administration to develop fuel cell powered vehicles. Both programs would be operated by the Department of Energy (DOE).

Under the President's plan, hydrogen would be consumed in automobiles powered not by internal combustion engines but by fuel cells. And because the sources of energy used to produce hydrogen would be domestic sources—like natural gas, coal, or renewable energy—converting to a "hydrogen economy" could greatly reduce our nation's dependence on foreign oil. According to the President, the Hydrogen Initiative will lead to a reduction in imported oil of 11 million barrels per day by 2040.

To successfully make the conversion to a hydrogen economy, the FreedomCAR and Hydrogen Initiatives must overcome several serious technical and economic challenges. There is no way, for example, to safely or economically store enough hydrogen on board an automobile to provide a driving range of 300 miles—the minimum that auto companies say consumers expect from a car. Also, if consumers are ever to purchase a hydrogen fuel cell powered car, an infrastructure much like that which exists for gasoline, with a fuel station every few blocks, may be necessary.

FreedomCAR

The FreedomCAR (for "Cooperative Automotive Research") program, upon which the Hydrogen Initiative expands, is a research partnership with Ford, General Motors, and Daimler/Chrysler. FreedomCAR itself arose out of an earlier program, called the Partnership for the Next Generation Vehicles (PNGV), begun under the Clinton Administration. FreedomCAR's goal is to reduce the cost and improve the efficiency of automotive components by 2010.

Hydrogen Roadmap

While FreedomCAR focuses on vehicle-specific technologies, the Hydrogen Initiative focuses on technologies for hydrogen production and the infrastructure necessary to deliver it. The Initiative itself is based on recommendations from the President's National Energy Policy and the National Hydrogen Roadmap.[1]

The roadmap was developed at a series of meetings sponsored by DOE that brought together stakeholders from various industries (including the automobile, petroleum, electric power, and fuel cell industries and industrial gas suppliers) and state and federal governments to discuss the challenges for a hydrogen economy. The roadmap, released in November 2002, identifies seven areas presenting specific challenges for a hydrogen economy:

- Reducing the cost of hydrogen production.
- Creating an expansive infrastructure to supply hydrogen.
- Lowering the cost and improving the performance of methods to store hydrogen.
- Reducing the cost of fuel cells.
- Developing applications for using hydrogen in consumer products (including not only automobiles, but also stationary fuel cells to power buildings and consumer products such as laptops and cell phones) with the same or better performance as conventional products.
- Educating the public about the environmental and energy security benefits and safety concerns.
- Developing model codes and standards, for buildings, for example, that would allow for the use of hydrogen as a fuel.

Next Steps

Relying heavily on the hydrogen roadmap, DOE is now creating a detailed research and development plan (which will be reviewed by the National Academy of Sciences). A few details have emerged about the overall focus of the Initiative, which according to DOE will focus on improving the technology in three critical areas: hydrogen storage, hydrogen production, and fuel cell technology.

According to DOE, to make hydrogen competitive with current technologies the Initiative must increase the performance of hydrogen storage technologies by a factor of three, reduce hydrogen production costs by a factor of four, and reduce fuel cell technology costs by a factor of ten. Achieving such goals will require breakthroughs in technology, rather than mere incremental advancements.

The Initiative will also expand DOE's currently-small programs to educate the public about hydrogen and to develop codes and standards to facilitate the adoption of hydrogen technologies. New codes and standards are particularly important as current regulations treat hydrogen as a hazardous material, and would likely be a significant barrier to widespread adoption.

DOE's goal is to advance hydrogen and fuel cell technologies to the point that would allow industry to make a decision by 2015 as to whether or not to bring those technologies to market.

Issues

While many interest groups, companies, and scientists support the development of technologies to allow the Nation to convert to an economy powered by hydrogen, the President's Initiative has left many questions unanswered.

What effect will the choice of fuel used to create hydrogen have on the environment, economy, and on energy security? Hydrogen is not a source of energy itself—like oil. Rather, like electricity, it must be made from sources of energy. For example, hydrogen can be produced by reforming natural gas or electrolyzing water using electricity generated from any other source of energy, including nuclear power. While hydrogen fuel cells produce no pollution, the use of coal to produce the hydrogen could result in greater emissions of carbon dioxide than combusting traditional fuels. Making hydrogen from electricity produced by wind power, while more expensive, would produce no such emissions. If oil were used, the country would realize little benefit in energy security. And finally, if natural gas were the main source of hydrogen, it could affect the price of other products in which natural gas is used, such as chemicals.

To assess the overall benefits and costs of hydrogen—and the multiple options for how it may be produced, transported, and stored—a complete life-cycle analysis (also called a well-to-wheels analysis) must be conducted. It is unclear, however, how DOE plans will incorporate such analyses.

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[1] www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

Will technological factors alone be enough to provide the incentives needed to convert to a hydrogen-based economy, or will policy changes be necessary? DOE's goal is to reduce the costs of hydrogen technologies so they are competitive with those of traditional fuels. Once the technologies reach this stage, DOE plans to allow industry to commercialize them. But the commercialization of fuel cell vehicles will never occur without the simultaneous development of an infrastructure to deliver hydrogen fuel. And, in a classic "chicken-and-egg" conundrum, the necessary infrastructure will never be built without a clear market for the hydrogen. Developing that infrastructure—an undertaking estimated to cost more than $200 billion—and encouraging simultaneous markets to use hydrogen, will clearly require government coordination and involvement.

Even after reducing the other hurdles to hydrogen use, hydrogen is still likely to cost more than conventional fuels unless government policies create significant incentives to use it. Those could include tax and other incentives, but the most effective tool would be through regulations that make clear the social costs (e.g., from pollution, greenhouse gas emissions, dependence of foreign sources of oil) of competing fuels. The Administration has given no sense of how policy tools figure in its plans to move to a hydrogen economy.

It is not clear what role policy considerations will play in DOE's plans to develop hydrogen technologies.

What is the likelihood all the technical challenges will be met? The number and magnitude of the technical challenges that must be overcome to enable a future economy based on hydrogen fuel are great. How to store hydrogen safely and at high densities presents enormous technical challenges. It is unknown whether it would make more sense to build large, centrally located facilities to produce hydrogen or place smaller hydrogen-production devices closer to the site where it will be used. Also, the capability does not now exist to produce large numbers of fuel cells cost competitively. It is unclear what benefits the Hydrogen Initiative would provide if some of these technical challenges prove insurmountable.

How does the Hydrogen Initiative affect funding for other programs? The FreedomCAR and Hydrogen Initiatives are expected to cost $1.7 billion over five years. The President called for $273 million for these programs in the FY04 request, an increase of $88 million over levels appropriated for existing hydrogen programs in FY03. However, this increase appears to have come largely at the expense of other energy efficiency and renewable energy programs. The two programs cut most significantly, which promote industrial efficiency and the use of biomass, could have near-term impacts on reducing both petroleum usage and emissions. Unless additional funding is provided to renewable energy and energy efficiency programs at DOE in general, the projected increases in the FreedomCAR and Hydrogen Initiatives will likely result in more cuts to such programs.

Legislation

The Committee has introduced legislation (H.R. 238), which includes provisions amending the Spark M. Matsunaga Hydrogen Research, Development and Demonstration Act of 1990 (42 U.S.C. 12401) and the Hydrogen Future Act of 1996 (42 U.S.C. 12403) (introduced and passed under the sole jurisdiction of the Science Committee), whose authorizations have expired. The text of H.R. 238 is largely based on language approved by the House and the Senate conferees as part of last year's energy conference negotiations, but disagreements on other issues in the bill prevented final passage. The witnesses have been asked to provide written comments and suggestions on the hydrogen language in H.R. 238, and be prepared to answer questions on the bill. A brief summary of those provisions is attached to this charter.

Witnesses

The following witnesses have been confirmed for the hearing:

1. David Garman, Assistant Secretary for Energy Efficiency and Renewable Energy, Department of Energy.
2. Alan C. Lloyd, Ph. D., 2003 Chairman, California Fuel Cell Partnership.
3. Joan Ogden, Ph.D., Research Scientist, Princeton Environmental Institute.
4. Dr. Larry Burns, Vice President, Research, Development and Planning, General Motors.
5. Don Huberts, Chief Executive Officer, Shell Hydrogen.

Questions to the Witnesses

The witnesses have been asked to address the following questions in their testimony:

David Garman:

- At a briefing earlier this year, the Department indicated that a posture plan for the hydrogen initiative was being developed at DOE. Please update us on the status of the plan. Does the plan contain specific budget structures and program goals? Will market penetration milestones be part of the program, or will the Department limit its strategic planning to technical milestones? What industry and stakeholder input is being solicited for the plan?
- What specific and comprehensive goals are needed for the hydrogen initiative to ensure the fastest possible development and widespread utilization of hydrogen? Does the department intend to create goals for the full range of hydrogen technologies, from production to utilization including stationary and mobile applications?
- What additional steps will DOE take to ensure that the benefits of this federally funded research effort reach average consumers in the shortest possible time?
- Is funding for the future expansion of the hydrogen initiative expected to come from within the Office of Energy Efficiency and Renewable Energy, or from other areas?
- Is life-cycle cost analysis being used to evaluate the various hydrogen technology options, such as including the cost of sequestration for hydrogen production from fossil fuels?

Alan C. Lloyd:

- What obstacles has the Partnership faced in putting hydrogen vehicles and infrastructure "on the ground"? How have you overcome these obstacles, and how do you plan to do so in the future?
- What elements should be included in the Department of Energy's hydrogen program to both effectively develop hydrogen technologies and promote their adoption?
- What are the greatest hurdles the country will face in converting to a hydrogen economy? To what extent is a federal effort needed to clear the way?

Joan Ogden:

- What are the most significant barriers to the widespread adoption of hydrogen as an energy carrier?
- You have written that, "Economics alone are unlikely to lead to a switch from current fuels to hydrogen.. . .If a hydrogen economy is implemented, it will be in response to strong political will." (From p. 74 of your *Physics Today* article). What types of policy tools will be necessary to ensure a transition to hydrogen? How should a research and development plan take these policy choices into account? When do we need to consider these policy options in order for them to be effective?

Larry Burns:

- In what time frame does GM expect hydrogen technology to become widely available? Does GM expect technology advances to make hydrogen technology cost-competitive with conventional technology? When?
- What technologies, including non-vehicle technologies, does GM see as the most promising for near-term use of hydrogen? Does GM plan to market any of those technologies?
- What does GM see as the federal role in the conversion to a hydrogen economy? How much is GM's own research dependent on federal involvement in the hydrogen research and development effort?
- The Department of Energy has indicated that the President's hydrogen initiative will allow industry to make a go/no-go decision on hydrogen technologies around 2015. Do you agree? What technical and policy factors will most influence GM's decisions on whether to rely on hydrogen technologies?

Donald Huberts:

- In what time frame does Shell Hydrogen expect hydrogen technology to become widely available? Do you expect technology advances to make hydrogen technology cost-competitive with conventional technology, and, if so, when? What are the greatest hurdles the U.S. faces in converting to a hydrogen economy? Can such a conversion occur absent government incentives or regulation?
- What technologies, including non-vehicle technologies, does Shell Hydrogen see as the most promising for near-term use of hydrogen? Does Shell Hydrogen plan to market any of those technologies?
- What can the U.S. Federal Government do to facilitate the development of and transition to a hydrogen economy? Is the Department of Energy's Hydrogen Initiative adequate? To what degree does Shell's own investments in hydrogen R&D depend upon the involvement of the U.S. Federal Government?

Chairman BOEHLERT. It is a pleasure to welcome everyone here this morning to the Congress' first hearing on the President's Hydrogen Initiative. I think the President deserves applause from across the political and ideological spectrum for his forward looking proposal. Whenever anyone thinks we should be doing right now to promote clean air and energy independence, we should all be able to agree that moving forward toward a hydrogen economy is what we need to strive for in the future. And the President has signaled in a forceful and prominent way that he is willing to commit the resources to help develop the technology for a hydrogen economy.

The Hydrogen Initiative is the kind of forward looking investment that the Science Committee has always promoted on a bipartisan basis. I look forward to adding the language to authorize the initiative in the Science Committee's portion of the comprehensive Energy Bill that is now slated to come before the House in the first week of April.

We have tentatively scheduled the Science Committee's markup of our portion of that bill, known as H.R. 238 on March 20.

I should note that industry also seems seriously committed to research and development work on hydrogen. I am pleased with the announcement that GM and Shell have just made about their joint efforts to develop and demonstrate hydrogen fueling and vehicles. We need to see how hydrogen might work in everyday settings in the real world.

But our enthusiastic support for the Hydrogen Initiative doesn't mean we don't have any questions about it. Both the Administration and Congress are going to have to do a lot more work to figure out exactly how to shape the Initiative. Here are some of the key questions we need to ask.

How will we pay for the incentive Initiative? Much of next year's proposed funding comes from cutting other renewable energy R&D programs. That is not acceptable.

What specific areas will the Initiative focus on and who will perform the research? We will have to choose among hydrogen sources and among different technologies. And we will have to decide where the federal contribution can do the most good.

What kinds of demonstration projects will truly advance the transition to a hydrogen economy? The projects need to be true tests of the technology, not one-of-a-kind distractions that never get replicated.

What policy tools will need to be deployed to enable the transition to a hydrogen economy and how will policy decisions affect the nature of the research that gets conducted now? No transportation revolution in American history has occurred without massive government involvement, whether that meant building canals, giving land to the railroads, developing aircraft and airports, or constructing the interstate highway system to name just a few examples. It would be absurd to think that hydrogen will be an exception.

I think that last point is critical. The magic of the marketplace alone is not going to create a hydrogen economy, at least not anytime soon. It addition to the huge technical hurdles, switching to hydrogen may entail enormous costs. We need to start thinking now about what policies will be necessary later because that may help determine which research areas the government might best invest in, and there must be investment.

Moreover, the regulatory climate will have an enormous impact on the timing and nature of the hydrogen economy. Hydrogen will be a cost-competitive fuel in the coming decades only if one takes into account the social costs of current fuels, such as the pollution they generate and the dependence on foreign oil they promote.

And the nature of future regulations will likely effect what sources of hydrogen we chose, and whether concerns about greenhouse gases have to be factored in to the design of hydrogen technologies. If we are going to make the right decisions about our research dollars now, we have to have a better idea of what our environmental concerns will be later.

So we have got a lot of tough thinking ahead of us. I am pleased that we have such a distinguished panel with us to help us get started. And I invite the panelists to take their places at the witness stand. Mr. Hall.

[The prepared statement of Mr. Boehlert follows:]

PREPARED STATEMENT OF CHAIRMAN SHERWOOD BOEHLERT

It's a pleasure to welcome everyone here this morning to the Congress' first hearing on the President's Hydrogen Initiative.

I think the President deserves applause from across the political and ideological spectrum for his forward-looking proposal. Whatever anyone thinks we should be doing right now to promote clean air and energy independence, we should all be able to agree that moving toward a hydrogen economy is what we need to strive for in the future. And the President has signaled in a forceful and prominent way that he is willing to commit the resources to help develop the technology for a hydrogen economy.

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Here are some of the key questions we need to ask:

1) How will we pay for the Initiative? Much of next year's proposed funding comes from cutting other renewable energy R&D programs. That's not acceptable.
2) What specific areas will the Initiative focus on and who will perform the research? We will have to choose among hydrogen sources and among different technologies, and we will have to decide where the federal contribution can do the most good.
3) What kinds of demonstration projects will truly advance the transition to a hydrogen economy? The projects need to be true tests of the technology, not one-of-a-kind distractions that never get replicated.
4) What policy tools will need to be deployed to enable the transition to a hydrogen economy and how will policy decisions affect the nature of the research that gets conducted now? No transportation revolution in American history has occurred without massive government involvement, whether that meant building canals, giving land to the railroads, developing aircraft and airports, or constructing the interstate highway system to name just a few examples. It would be absurd to think that hydrogen will be an exception.

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So, we've got a lot of tough thinking ahead of us. I'm pleased that we have such a distinguished panel with us today to get us started. Mr. Hall.

Mr. HALL. Mr. Chairman and Members of the Committee, thank you. It seems like it is only last week that we were in conference on energy legislation after more than a year and a half of working out how to get a comprehensive match on energy policy. These efforts failed, but they didn't fail because of any lack of duties of this committee. They didn't fail because of any lack of duty of the House itself. We passed the Bill, sent it over to them; we were in Session for day and night for a long, long time and came up with a zero. I think that legislation again this time, the very comprehensive research and development section of that bill could become the centerpiece of the legislation had it passed. And one good thing about that bill was that we have a President and a Vice President that understand energy. And we have a President and a—a President who will sign that type of legislation if we get it to him.

So, I look forward to working with you in the weeks ahead to recreate the legislation with the hope and expectation that this time we are going to put a bill with their provisions in it and on the President's desk. Today, we have a hearing on hydrogen and it is appropriate that we start there since the President has announced new initiatives in that area.

Last year, the Department of Energy rolled out the FreedomCAR Program to develop the technologies necessary to produce the hydrogen powered vehicles. We were concerned about the Department not paying sufficient attention to the infrastructure issues, and apparently they heard us because this year they are rolling out infrastructure programs, the Freedom Fuel Program.

It is clear to me that without a hydrogen fuel infrastructure, these vehicles will never hit the streets, and we will never be able to realize that all the emissions savings possible unless we make the commitment to develop a hydrogen infrastructure.

There are huge unanswered questions associated with the proposed infrastructure. Many of these questions, as you have stated very well, will involve costs and safety. Other questions center around how it is going to be setup. For example, will we rely on pipelines, or tank trucks, or tank cars to transport the hydrogen? Will it be distributed on a more centralized system to be developed?

We hope to get into many of these type of questions with the fine panel we have here today. Before I yield time to Mr. Lampson, I want to thank the panel for being with us today and on such short notice. We look forward to receiving your testimony and appreciate your helping us to understand better these complexes. With that, Mr. Chairman, I need to yield just a minute or so, or two minutes, or five minutes, or 10 minutes to Nick Lampson for any comments he may have. I ask your unanimous consent that the rest of the Committee urge you to grant that permission.

Chairman BOEHLERT. In the spirit of bipartisan cooperation, I am pleased to grant it.

Mr. HALL. After all of my things I said, I get a little something out of that, don't I?

Chairman BOEHLERT. The gentleman's time is extended for two additional minutes.

Mr. LAMPSON. How about 30 seconds will be fine, Mr. Ranking Chairman; I thank you. And Mr. Chairman, I appreciate the time. I come from Southeast Texas, which has sometimes been called the energy capital of the world, so it is a real privilege to be able to serve as a ranking Member on the Science Energy Committee. And I am particularly pleased with what we are getting ready to listen to this morning on the use of hydrogen, because we do produce so much hydrogen in that area. As we learn how to distribute this across the country I think it is going to be something extremely important for that area that continues to be the energy capital of the world.

So I just wanted to add my thanks and appreciation for the panel to be coming, and I look forward to what you have to say. And I yield back my time. Thank you, Mr. Chairman.

[The prepared statement of Mr. Burgess follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL C. BURGESS

Thank you Mr. Chairman, and thank you for having this hearing.

With global oil reserves low after a two-month Venezuelan strike and trepidation about the effect on oil prices of a possible war with Iraq, gas prices are extremely high. The United States is especially vulnerable to international price fluctuations since we import approximately 55 percent of the oil we consume daily from foreign sources. Americans are reminded of the need for energy independence every time we pay exorbitant prices to fill up our cars.

President Bush, during his State-of-the-Union Address, proposed a bold FreedomCAR and Hydrogen Fuel Initiative and estimated that the first car driven by a child born today could be powered by hydrogen technology. The President's budget would allow $1.2 billion in research funding for hydrogen-powered automobiles and hydrogen fuel technology.

The goal of this new FreedomCAR program is to make hydrogen fuel cell technology a viable, affordable and convenient technology that we can use to power our automobiles. There are many benefits, including a cleaner environment, the possibility that research can spur further technological innovation, and especially greater energy independence.

As a member of both the Science and Transportation and Infrastructure Committees, I recognize the unique challenges that we face as we discuss the possibility of converting into a hydrogen-fueled economy. We must discuss the appropriate role for the Federal Government in this process and examine our focus on FreedomCAR and hydrogen-based infrastructure, but we must do so within the context of a comprehensive energy policy. Our approach to energy policy must be comprehensive in nature so that we ensure achievement of our goal of national energy independence. In addition, we must also take seriously our responsibility to ensure that taxpayer dollars are spent wisely and must keep this in mind as we discuss the President's Hydrogen Initiative.

So, again, Mr. Chairman, I thank you for this hearing in which we can address some our concerns.

[The prepared statement of Mr. Costello follows:]

PREPARED STATEMENT OF REPRESENTATIVE JERRY F. COSTELLO

Good morning. I want to thank the witnesses for appearing before our committee to discuss the President's Hydrogen Initiative, which is intended to lay the foundation necessary for making the transition to an economy powered by hydrogen. The President's Hydrogen Initiative envisions the transformation of the Nation's transportation fleet from a dependence on foreign oil and petroleum to the use of clean-burning hydrogen. Today, most hydrogen in the United States and about half of the world's hydrogen supply is produced from natural gas.

However, the President plans to change this. On February 27, 2003, the President announced his Integrated Sequestration and Hydrogen Research Initiative entitled FutureGen. This project is a $1 billion government/industry partnership to design, build, and operate a nearly emission-free, coal-fired electric and hydrogen production plant. The prototype plant will serve as a large-scale engineering laboratory for testing and will expand the options for producing hydrogen from coal.

As the Administration begins to consider locations for the new plant, I would hope they would consider Southern Illinois. The region is rich in high-sulfur coal reserves and the Coal Center at Southern Illinois University Carbondale (SIU–C) has been doing extensive work with hydrogen and coal. In addition, the geology of the region is well suited to the carbon-trapping technology to be developed. Carbon dioxide could be captured and sequestered in underground geological formations called aquifers. I am particularly interested in hearing from our witnesses the benefits of this new program and a timeline or target goal for expecting results.

A greater reliance on hydrogen requires modification of our existing energy infrastructure to ensure greater availability of this new fuel source. The President's Initiative has left many questions unanswered, but I am hopeful our witnesses here today will provide more insight into the funding and technology challenges facing the Hydrogen Initiative.

I again thank the witnesses for being with us today and providing testimony to our committee.

Chairman BOEHLERT. Thank you, very much. With that, let us get right off with our very distinguished panel. This is the first hearing any place on Capitol Hill about this hydrogen initiative, and we have an expert panel of witnesses that I look forward to hearing from, consisting of David Garman, Assistant Secretary for Energy Efficiency and Renewable Energy at the U.S. Department of Energy, Dr. Alan C. Lloyd, 2003 Chairman for the California Fuel Cell Partnership, Dr. Lloyd. Dr. Joan Ogden, Research Scientist, Princeton Environmental Institute. Dr. Larry Burns, Vice-President, Research Development and Planning for General Motors. And Don Huberts, Chief Executive Officer for Shell Hydrogen. We look forward to your testimony. We ask that you summarize in five minutes or so. The Chair is not going to be arbitrary on that. This is too important a subject to let 300 seconds be sufficient to have you say what you need to say to all of us, but we look forward to a very valuable and informative hearing. We start with you, Mr. Garman.

STATEMENT OF DAVID K. GARMAN, ASSISTANT SECRETARY FOR ENERGY EFFICIENCY AND RENEWABLE ENERGY, U.S. DEPARTMENT OF ENERGY

Mr. GARMAN. Thank you, Mr. Chairman, and thank you for this opportunity to discuss the advantages of a hydrogen energy economy and the pathway that gets us there. We envision a day when energy can be affordable, abundant, reliable, virtually pollution free, and carbon neutral. And the President's National Energy Plan explicitly recognizes the role that hydrogen can play.

The President's Plan was released in May 2001, and important elements of that Plan related to hydrogen have been expanded upon with the FreedomCAR Partnership, announced in January

2002, the President's Hydrogen Fuel Initiative announced during his recent State of the Union Address, and the FutureGEN zero-emission coal fired electricity and hydrogen power plant initiative announced just last week. Mr. Chairman, your Committee has really demonstrated some key leadership on hydrogen. And by my count, I think I have appeared five times on hydrogen or hydrogen related technology in the last 19 months.

Chairman BOEHLERT. I give you frequent appearance points.

Mr. GARMAN. With your guidance and under your Oversight, we have worked with industry, academia, the environmental community, and other stakeholders over the last two years to build a strong analytical foundation for these initiatives. And if I could just put it bluntly another way, these ideas were not cobbled together on the way to the podium for the State of the Union message. Instead, they converged to make possible a future where the primary energy carriers in our economy are hydrogen and electricity, eventually generated using technologies that do not emit any pollutants or carbon dioxide.

We don't want to become overly dependent on any one method of generating electricity or hydrogen, and the advantage of hydrogen is that it can be produced from a variety of primary energy sources, including renewables, nuclear, and fossil energy. And the question why hydrogen and why now? One real driver for change is the situation that confronts us with regard to oil dependence in the transportation sector. The current gap between total U.S. consumption and net production-able oil is roughly 11 million barrels per day. And this is a gap that we are unable to close with either regulation, or new domestic production, or even both. Although promoting efficiency in the use of oil and finding new domestic sources of oil are important short-term undertakings, under the long-term a petroleum free option is eventually required.

That is why the President, during his State of the Union Address, announced a ground breaking plan to transfer our nation's energy future from one dependent on foreign petroleum to one that utilizes hydrogen, which is the most abundant item in the universe. He has challenged us to be bold and innovative, to change our dependence on foreign energy, and to do this through hydrogen fuel cells.

So our work is underway in earnest. And fortunately, we are not starting from scratch. We have a technology roadmap, a recently completed fuel cell report to Congress, regular progress reporting, and an internal posture plan, all of which have been in development for the past year or longer. Many on this panel have been participants in the development of some of these plans. And frankly, we realize that this is an initiative that is beyond the political time horizon of this Administration, and we have to lay a solid foundation for future Administrations that follow. So we want to be transparent and accountable in our planning, and we expect to achieve results.

I will attempt to summarize these documents in just two slides.

[Slide]

Mr. GARMAN. First, we envision the transition of a hydrogen economy occurring in four phases. In phase one, government and private organizations will research, develop, and demonstrate critical path technologies prior to investing heavily in infrastructure. This phase is now underway and will enable the industry to make a decision on commercialization on vehicles in 2015. The Fiscal Year 2004 Budget currently before Congress currently is consistent with the completion of a technology R&D phase by 2015.

In phase two, transition of the marketplace could begin as early as 2010 for applications such as portable power and some stationary applications, and even earlier in rich applications where hydrogen related technologies meet or exceed consumer requirements. If an industry decision to commercialize fuel cell vehicles is made in 2015, mass market penetration of these vehicles can occur in 2020. As these markets become established, government can foster further growth by playing the role of early adopter and by creating policies that stimulate the market.

As markets are established, this leads to phase three, expansion of markets and infrastructure. The start of phase three is consistent with the positive commercialization decision in the year 2015. That will attract investment and infrastructure for fuel cell manufacturing, hydrogen production and delivery.

And phase four, which will begin around 2025 is the realization of the hydrogen vision, when consumer requirements will be met or exceeded, national benefits in terms of energy security and improved environmental quality are being achieved, and industry can achieve adequate return on investment and compete globally.

If the transition unfolds as we have envisioned, this graph illustrates what happens to oil demand in the light duty vehicle category and when it happens. This scenario results in 11 million barrels per day by 2040 compared to what would otherwise be consumed in that year. We currently import today between 10 and 11 million barrels per day.

Mr. Chairman, the path to a hydrogen economy is guided by a strong national commitment by the President and by leaders in Congress, a diversified technology portfolio, and an approach that relies on public/private partnership. We are excited about the prospects for this future, and we look forward to working with Congress, and this committee, and the private sector to make it happen. Thank you, Mr. Chairman.

[The prepared statement of Mr. Garman follows:]

PREPARED STATEMENT OF DAVID K. GARMAN

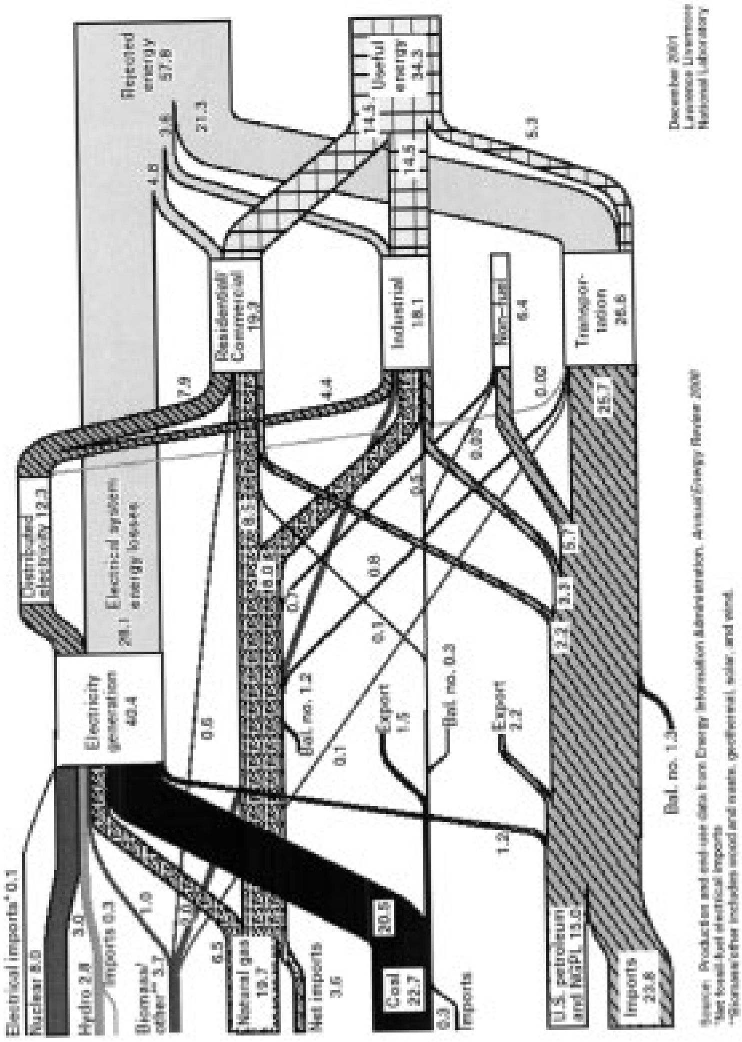
Mr. Chairman, Members of the Committee, I appreciate the opportunity to testify before you today on “The Path to a Hydrogen Economy.”

Energy is the life-blood of our nation. It is the mainstay of our standard of living, our economy, and our national security. The President’s National Energy Plan, entitled “Reliable, Affordable and Environmentally Sound Energy for America’s Future,” is the blueprint for the energy future we seek, and it makes several recommendations with regard to hydrogen. Specifically, it directs the Secretary to develop next generation energy technology, including hydrogen; it recommends that our research and development (R&D) programs related to hydrogen and fuel cells be integrated; and it recommends that legislation reauthorizing the Hydrogen Energy Act enjoy the support of the Administration.

Since the release of the President’s energy plan in May 2001, the President and Secretary Abraham have unveiled several exciting new initiatives related to hydrogen. Most notable are the FreedomCAR partnership announced in January 2002; the President’s Hydrogen Fuel Initiative announced during the State of the Union address in January 2003; and the “FutureGEN” zero-emission coal-fired electricity and hydrogen power plant initiative announced just last week. Each of these initiatives plays a particularly important role in a hydrogen energy future. Each will help make possible a future in which the principal "energy carriers" are hydrogen and electricity, eventually generated using technologies that do not emit any pollutants or carbon dioxide.

Our present energy picture is significantly different than a potential hydrogen energy future. A diagram developed by Lawrence Livermore National Laboratory [Figure 1] represents the current "energy flows" in the U.S. economy. It should not be regarded as a highly precise representation of these flows, but it is extremely useful in helping policy-makers visualize complex energy data.

Figure 1: Current Energy Flows



December 2001
Lawrence Livermore
National Laboratory

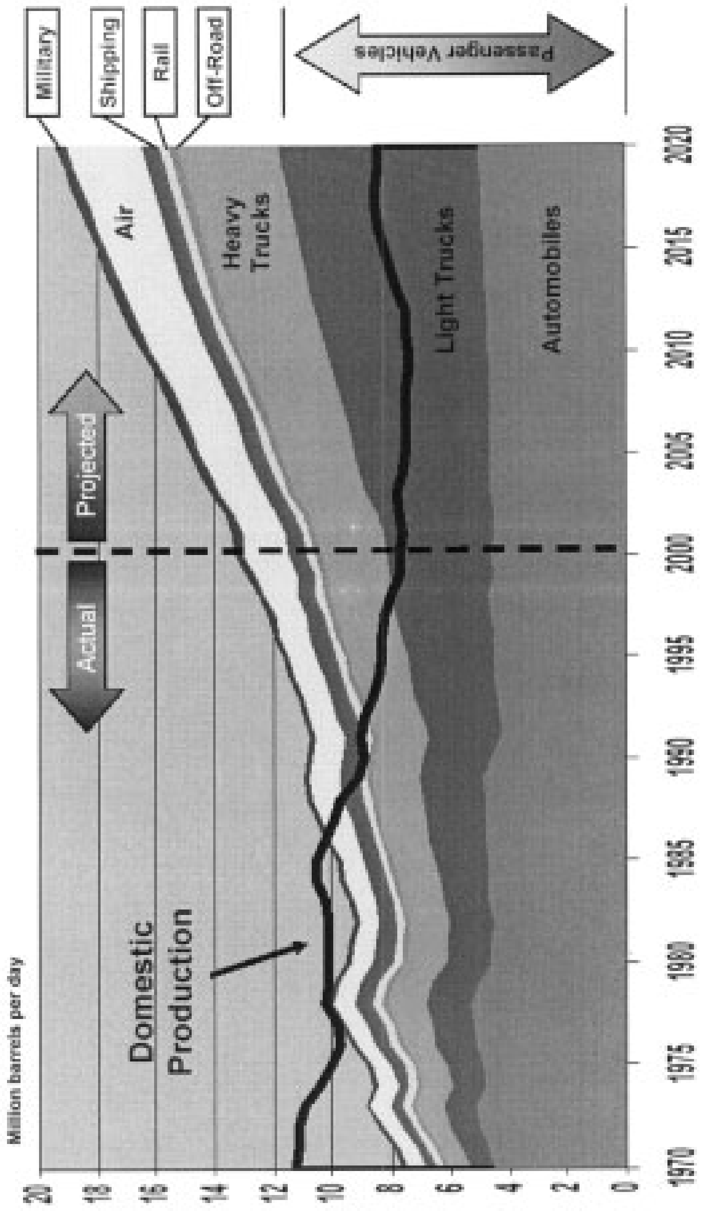
Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2000*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood and waste, geothermal, solar, and wind.

The primary energy inputs, including coal, oil, natural gas, nuclear, and renewable energy are shown on the left. The relative sizes of the lines or "pipes" represent the relative contributions of the primary energy inputs, the impacts of energy conversion, and the end uses.

Using this it is easier to visualize how the energy flows move toward electricity generation or through the different sectors of our economy. The diagram makes clear some inescapable features of our current energy economy:

- We enjoy a diversity of primary energy inputs, although there are imbalances;
- We are heavily dependent on oil, coal, and natural gas;
- The transportation sector is almost entirely dependent on oil, a majority of which is imported;
- A large amount of energy is rejected or wasted, and transportation is the least efficient of the three sectors of our energy economy;
- Looking more specifically at oil as we do in the next graph [Figure 2] we see that there is an imbalance between petroleum demand for transportation and domestic production, and that automobiles and light trucks are the dominant driver behind that demand.

Figure 2: Oil Use in Transportation Plotted against Domestic Production



In the early 1990s, the petroleum required just by our highway vehicles surpassed the amount produced domestically. The "gap" between production and transportation demand is growing—and is projected to keep growing. The current gap between total U.S. consumption and net production of oil is roughly 11 million barrels per day. Promoting efficiency in the use of oil, and finding new domestic sources of oil, are both important short-term undertakings. But over the long-term, a petroleum-free option is eventually required.

Our energy challenge is further complicated by another important factor—the pollutants and carbon dioxide emissions resulting from our use of energy. We have made tremendous progress in reducing pollutant emissions from our cars and trucks as well as our stationary power sources, and we will continue to make incremental gains through regulatory approaches such as the Tier II standards. But for true efficiency gains, we must reach to develop a wholly new approach to energy.

In his recent State of the Union address, President Bush announced a groundbreaking plan to transform our nation's energy future from one dependent on foreign petroleum, to one that utilizes the most abundant element in the universe—hydrogen.

Hydrogen can be produced from diverse domestic sources, freeing us from a reliance on foreign imports for the energy we use at home. Hydrogen can fuel ultra-clean internal combustion engines, which would reduce auto emissions by more than 99 percent. And when hydrogen is used to power fuel cell vehicles, it will do so with more than twice the efficiency of today's gasoline engines—and with none of the harmful air emissions. In fact, fuel cells' only byproducts are pure water and some waste heat.

But ultimate success in the mass-market penetration of hydrogen fuel cell vehicles requires a hydrogen-based infrastructure that performs as well as the petroleum-based infrastructure we now have.

Our current gasoline/hydrocarbon infrastructure has been forged in a competitive market. It is ubiquitous and remarkably efficient. It can deliver refined petroleum products that began as crude oil half a world away to your neighborhood for less than the cost of milk, drinking water, or many other liquid products you can buy at the supermarket. We are currently bound to that infrastructure. We have no alternative. Eventually replacing it with something different will be extremely difficult. But that is what we must do if we expect to achieve success with the FreedomCAR partnership. Drivers must be able to go anywhere in America and to refuel their hydrogen-powered vehicle before they will be comfortable purchasing one.

That is why the President, in his State of the Union address, proposed that we in the Federal Government significantly increase our spending on hydrogen infrastructure R&D, including hydrogen production, storage, and delivery technologies, as well as fuel cells. Over the next five years, we plan to spend an estimated $1.7 billion on the FreedomCAR partnership and Hydrogen Fuel Initiative, $1.2 billion of which is for the Hydrogen Fuel Initiative, which includes resources for work on hydrogen and fuel cells. Of the $1.2 billion figure, $720 million is "new money."

We will not build the infrastructure. The private sector will do that as the business case becomes clear. But as we develop the technologies needed by the vehicles, we will also develop the technologies required by the infrastructure. In cooperation with DOT, we will convene the parties needed for technology partnerships, we will collaborate on the needed codes and standards, and we will promote international cooperation in this effort.

There is growing worldwide interest in hydrogen and fuel cell technology, as reflected in the dramatic increase in public and private spending since the mid-1990s in the U.S. and elsewhere. We estimate current investments across the U.S. government agencies to be well over $200 million, about $120 million of which is for hydrogen and polymer electrolyte membrane (PEM) R&D. In 2003, the Japanese government nearly doubled its fuel cell R&D budget to $268 million, and in March 2003 will launch a joint government/industry demonstration of hydrogen fuel cell vehicles, including the deployment of more than seven new hydrogen refueling stations. Governments and companies in Canada, Europe, and Asia are also investing heavily in hydrogen research, development and demonstration. For example, ten new hydrogen refueling stations will be built in Europe over the next few years to fuel hydrogen-powered buses. By comparison, the U.S. currently has approximately ten hydrogen refueling stations, and plans several more as appropriate to fund limited "learning" demonstrations to help identify R&D needs to make hydrogen and fuel cell technologies cost competitive and technologically viable.

Understandably, there is an aspect of economic competitiveness to all this as well. A recent report by PricewaterhouseCoopers projects global demand for all fuel cell products (in portable, stationary, and transportation power applications) to reach $46 billion per year by 2011 and to grow to more than $2.5 trillion per year in 2021. The United States should strive to be a leader in hydrogen and fuel cell technology development and commercialization in order to secure a competitive position for future energy technology innovations, new products, and service offerings. Without a change in direction, the more than 19 million barrels per day of petroleum projected to be imported to the U.S. by 2025 will cost our economy an estimated $188 billion per year (based on EIA projections) in real 2001 dollars.

Consistent with the questions posed by the Committee in its letter of February 20, 2003, I will now elaborate further on our approach, the benefits we expect, the technology challenges we face, the timing of the transition toward a hydrogen economy, and the budget we believe is needed to meet our goals.

Approach

In November 2001, about the time I was first testifying before this committee on the subject of hydrogen, we began a formal hydrogen vision and "roadmapping" effort. Working with industry, stakeholders and academia, the Department developed a national approach for moving toward a hydrogen economy—a solution that holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from domestic resources.

To realize this vision, the Nation must develop advanced technologies for hydrogen production, delivery, storage, conversion, and applications. The National Hydrogen Energy Technology Roadmap, which we released in November 2002, identifies the technological research, development, and demonstration steps required to make a successful transition to a hydrogen economy.

This past fall, the Department also developed an internal Hydrogen Posture Plan (Plan) to support the President's Hydrogen Fuel Initiative. The Plan identifies specific technology goals and milestones that would accelerate hydrogen and fuel cell development to enable an industry commercialization decision by 2015. My Office of Energy Efficiency and Renewable Energy led the development of the plan in collaboration with the Office of Fossil Energy, the Office of Nuclear Energy, the Office of Science and the DOE's Office of Management, Budget, and Evaluation.

The Plan integrates the Department's planning and budgeting for program activities that will help turn the concept of a hydrogen-based economy into reality. More specifically, the Plan outlines the Department's role in hydrogen energy R&D in accordance with the National Hydrogen Energy Roadmap. The Plan is currently in draft and under policy review. The development of the plan could not directly involve industry and other non-government stakeholders because of the inclusion of fiscal year 2004 through 2008 budget planning. Their input to other efforts such as the Hydrogen Roadmap, the Hydrogen Vision, the FreedomCAR Partnership Plan, and the Fuel Cell Report to Congress (which included four workshops with industry) has been considered in the development of the Posture Plan.

To ensure that the Department continues to conduct its hydrogen research in a coordinated, focused, and efficient manner, the DOE Hydrogen Working Group that developed the Posture Plan will continue to function. This Working Group will be chartered to meet regularly and perform the following functions:

- Evaluate the progress of the Department's hydrogen and related activities with regard to milestones and performance goals;
- Strengthen information exchange on technical developments;
- Help ensure that the various activities (e.g., budgeting, execution, evaluation, and reporting) remain well coordinated;
- Provide suggestions for management improvements and stronger technical performance; and,
- Coordinate, through the Office of Science and Technology Policy, with other agencies (e.g., DOD, DOT, NASA, Commerce) conducting similar R&D activities to ensure our efforts our complementary and not duplicative.

In anticipation of an energy bill this year, the Department is also preparing to form a Hydrogen Technology Advisory Committee (HTAC). This advisory group, composed of a diverse group of experts from industry, academia, and other stakeholders, would provide input to the Secretary.

My testimony today draws heavily from DOE's planning efforts including the Posture Plan, the FreedomCAR Partnership Plan, the Hydrogen Roadmap, and the Fuel Cell Report to Congress. These documents describe how DOE will integrate its ongoing and future hydrogen R&D activities into a focused Hydrogen Program. The program will integrate technology for hydrogen production (from fossil, nuclear, and renewable resources), infrastructure development (including delivery and storage), fuel cells, and other technologies supporting future hydrogen fueled vehicles. Successful implementation of the Administration's integrated plans and activities is critical to the FreedomCAR partnership and Hydrogen Fuel Initiative. Coordinating hydrogen activities within DOE and among the federal agencies will improve the effectiveness of our research, development, and demonstration (RD&D) activities and strengthen its contribution to achieving the technical milestones on the road to a hydrogen economy.

Benefits

The Administration has committed to a large investment in hydrogen and fuel cells because it is convinced that the potential benefits of moving to a hydrogen economy are enormous. We can eventually eliminate our dependence on foreign energy sources. We can also maintain our transportation freedoms, the mobility that is so important to our quality of life and healthy economy. We can dramatically improve our air quality by eliminating polluting emissions from vehicles. Finally, hydrogen-powered vehicles can benefit our economy by reducing the financial drain associated with foreign energy purchases and by sustaining a strong international competitiveness in the transportation arena.

The development of hydrogen and fuel cells promises clear economic and environmental benefits to the United States. Diversifying our energy resources, particularly through the expansion of hydrogen in transportation, will stimulate new markets and strengthen U.S. flexibility and economic resiliency in many other sectors. Achievement of hydrogen technology goals, complemented by supportive regulations and policies, will pave the way for hydrogen's rapid growth as an energy carrier over the next several decades. The full extent of life-cycle cost and environmental benefits will become clearer as development and validation progresses with respect to the various production, conversion and distribution options.

To be successful we must make sure that we not only overcome the technical barriers, but also that these technologies are affordable and accessible to the average consumer. It will only be through a sweeping, market-driven replacement of current technologies that the desired societal benefits can be reached.

Essential to rapid success and full technology utilization is the involvement of those industries that will have critical roles in the decisions to commercialize and in the manufacture of the necessary products. The development effort is shared by industry, both the automotive manufacturers and the energy companies, through their participation in the FreedomCAR Partnership and in the Hydrogen Fuel Initiative.

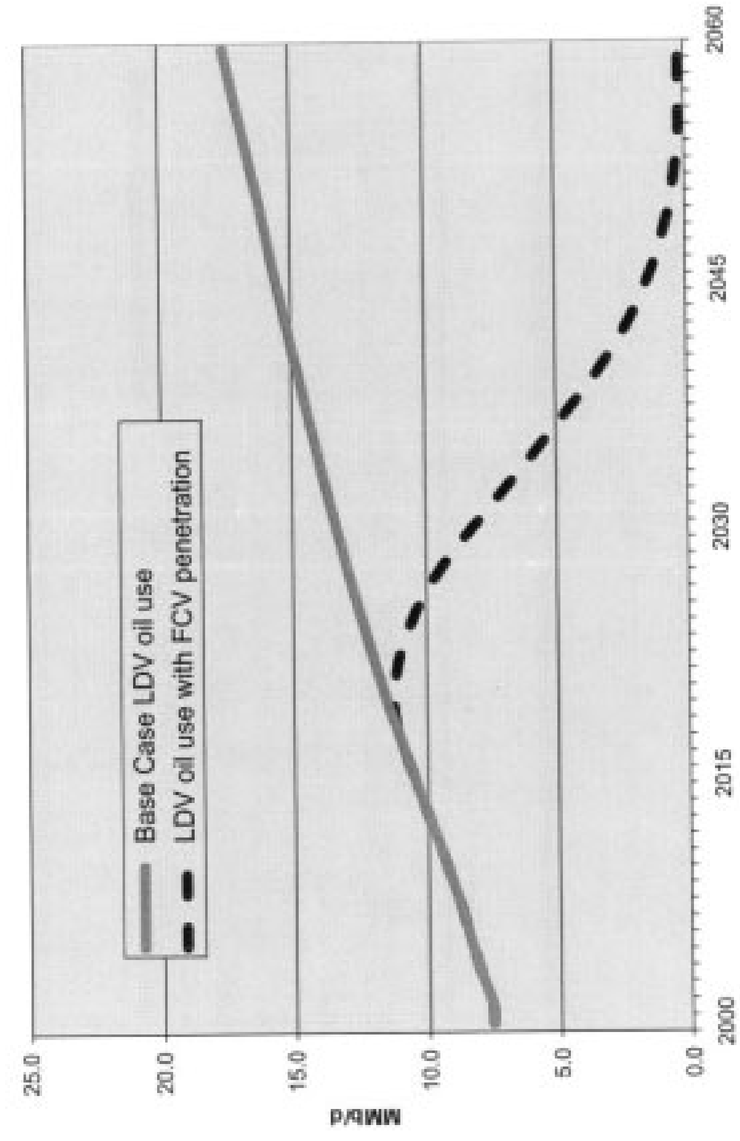
Energy Diversity

Hydrogen can be supplied in large quantities from domestic fossil, nuclear and renewable resources. This mix of currently available and developing technology could provide a transition from traditional to next generation energy technologies benefiting society with reliable and affordable energy in the near- and long-term. Hydrogen and fuel cells can catalyze the establishment and utilization of a viable transportation market for nuclear energy, domestic coal supplies, and renewables. [Carbon capture and sequestration can further reduce emissions from high carbon sources of hydrogen such as coal.] The fact remains, though, that our nation possesses the necessary resources to produce large quantities of hydrogen.

Transportation

Every day, eight million barrels of oil are required to fuel the over 200 million vehicles that constitute our light duty transportation fleet. By 2025, the Nation's light vehicle energy consumption is projected to grow to as much as 14 million barrels per day of petroleum or its energy equivalent. Fuel cell vehicles could provide more than twice the efficiency of conventional vehicles. Figure 3 shows a projection of the possible effect of introducing hydrogen-fueled vehicles on our nation's oil consumption. With the assumptions used in this scenario, hydrogen fueled fuel cell vehicles could make dramatic reductions in petroleum use. This scenario results in 11 million barrels per day savings by 2040 compared to what would otherwise be consumed in that year.

Figure 3: Light Duty Fuel Cell Vehicle Penetration Scenario



The Federal Government's role is to accelerate hydrogen and fuel cell development to enable industry to make a commercialization decision by 2015. But the manufacture and marketing of hybrid, fuel cell or other advanced vehicles will be industry's responsibility. The government's role, however, can be broader than the removal of technical barriers and the reduction of technology costs. In cooperation with DOT, we can also contribute to the pace of both industry and market acceptance by overcoming institutional barriers such as those associated with achieving common codes and standards necessary for safe use of hydrogen and fuel cell technologies.

Fuel Cells for Stationary Power

Hydrogen can also be used in stationary fuel cells, engines and turbines to produce power and heat. In order to meet our growing electrical demands, the Energy Information Administration estimated that electricity generation will have to increase by two percent per year (EIA Annual Energy Outlook 2002). At this rate, 1.5 trillion kWh of additional electricity generation capacity will be needed by 2020. Along with aging infrastructure, requirements for reliable premium power, and market deregulation, this increasing demand opens the door for hydrogen power systems and potential societal benefits. For example, using ten million tons of hydrogen per year to provide 150 billion kWh of the Nation's electricity (just ten percent of the added generation) could avoid 20 million tons per year of carbon dioxide emissions. DOE will also support work in the area of fuel cells for portable power. While not important to overall petroleum reduction, these units will provide early operating and manufacturing experience, and should contribute to the reduction of fuel cell cost for PEM fuel cells.

Technology Challenges

Let me now review the challenges to be faced and how these challenges are to be met. Achieving our vision will require a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. Success will not happen overnight, or even over years, but rather over decades; it will require an evolutionary process that phases hydrogen in as the technologies and their markets are ready. Success will also require that the technologies to utilize hydrogen fuel and the availability of hydrogen occur simultaneously.

Some of the significant hurdles to be cleared include:

- Lower by a factor of four the cost of producing and delivering hydrogen;
- Develop more compact, light weight, lower cost, safe, and efficient hydrogen storage systems that will enable a greater than 300 mile vehicle range;
- Lower by a factor of ten the cost of materials for advanced conversion technologies, especially fuel cells;
- More effective and lower cost (by a factor of at least ten) carbon-capture and sequestration processes (a separate program critical to fossil-based production of hydrogen);
- Designs and materials that maximize the safety of hydrogen use; and,
- The development of needed codes and standards as well as the education of consumers relative to the use of hydrogen.

The Department has drafted a work breakdown structure associated with each of the critical areas identified in the Roadmap (production, delivery, storage, conversion, and end-use), and has identified milestones and decision points that are part of the effort. Examples of key program milestones that support FreedomCAR and achievement of a hydrogen economy include the following:

- Onboard hydrogen storage systems with a six percent capacity by weight by 2010; more aggressive goals are being established for 2015;
- Hydrogen production at an untaxed price equivalent to $1.50 per gallon of gasoline at the pump by 2010;
- Polymer electrolyte-membrane automotive fuel cells that cost $45 per kilowatt by 2010 and $30 per kilowatt by 2015 and meet 100,000 miles of service life; and,
- Zero emission coal plants that produce hydrogen and power, with carbon capture and sequestration, at $0.79 per kilogram at the plant gate.

In the near future, we plan on partnering with energy companies to establish more specific goals related to technology and components needed to produce and distribute hydrogen using various fossil, nuclear and renewable pathways. In this exercise, we will be looking at the full range of hydrogen technology areas covered in the Roadmap.

Advances in other technologies will also be necessary for the ability of a hydrogen-fueled vehicle to realize its full potential. These include:

- Improved energy storage, (e.g., batteries that are more durable, cheaper, and better performing);
- More efficient and cost effective electric motors;
- Inexpensive and more effective power electronics; and,
- Better materials for lighter, but strong, structural members.

These technologies will enable hydrogen-fueled vehicles to be more efficient, and to help lower the vehicle cost to the consumer.

In the near- to mid-term, most hydrogen will likely be produced by technologies that do not require a new hydrogen delivery infrastructure (i.e., from distributed natural gas). As RD&D progresses along renewable, nuclear, and clean coal and natural gas production pathways (including techniques for carbon sequestration) a suite of technologies will become available in the mid- and long-term to produce hydrogen from a diverse array of domestic resources. The economic viability of these different production pathways will be strongly affected by regional factors, such as feedstock availability and cost, delivery approaches, and regulatory environment.

For hydrogen to become a viable fuel, advanced hydrogen storage technologies will be required, especially for automotive applications, where a driving range of at least 300 miles is needed. Current storage systems are too heavy, too large, and too costly. Technologies to convert hydrogen into useful energy—fuel cells and combustion technologies—must also be further improved to lower cost and improve performance.

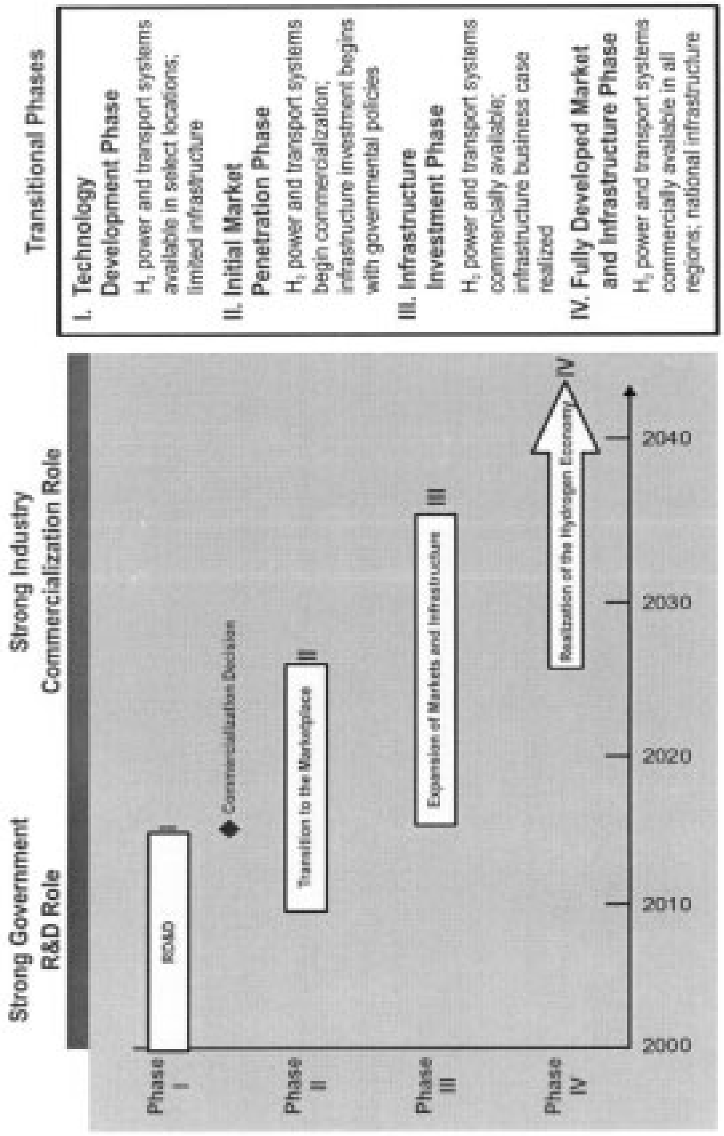
Detailed analysis of life-cycle costs and benefits for alternative hydrogen production pathways, carbon sequestration, and other elements will continue. "Well-to-Wheels" analyses conclude that the energy and environmental benefits depend greatly on how hydrogen is manufactured, delivered and stored, and on the economic feasibility of sequestration for fossil feed stocks. The results of these studies will help in making down-select decisions and to ensure that the relative merits of specific hydrogen pathways are evaluated properly and in comparison with other energy alternatives. Out-year planning will identify needs for RD&D on production and storage technologies, delivery infrastructure, and education and safety/codes and standards. Public education of consumers and local code officials must also be pursued concurrently with the RD&D.

Finally, industry must develop and construct the infrastructure to deliver hydrogen where it is needed. We will work with the DOT to help industry develop a safe, efficient, nationwide hydrogen infrastructure. The hydrogen distribution infrastructure can evolve along with the conversion and production technologies, since much of the infrastructure that is developed for fossil-based hydrogen will also be applicable to renewable- and nuclear-based hydrogen. We will partner with industry to develop infrastructure in pilot projects, and industry will expand locally, regionally, and ultimately nationally.

Transition to a Hydrogen Economy

We consider the transition to the hydrogen economy as occurring in four phases, each of which requires and builds on the success of its predecessor, as depicted in Figure 4. The transition to a hydrogen-based energy system is expected to take several decades, and to require strong public and private partnership. In Phase 1, government and private organizations will research, develop, and demonstrate "critical path" technologies and safety assurance prior to investing heavily in infrastructure. This Phase is now underway and will enable industry to make a decision on commercialization in 2015.

Figure 4: The Transition to the Hydrogen Economy



The FY04 Budget currently before Congress is consistent with completion of the technology RD&D phase by 2015.

Phase II, Transition to the Marketplace, could begin as early as 2010 for applications such as portable power and some stationary applications, and as hydrogen-related technologies meet or exceed customer requirements. If an industry decision to commercialize hydrogen fuel cell vehicles is made in 2015, mass-market penetration can occur around 2020. Consumers will need compelling reasons to purchase these products; public benefits such as high fuel use efficiency and low emissions are not enough. The all-electronic car powered by hydrogen fuel cells (such as the General Motors Hy-wire) is one example of an approach to greater value delivery; it could offer the consumer improved performance through elimination of mechanical parts and greater design flexibility through the "skateboard" approach with "snap-on" bodies.

As these markets become established, government can foster their further growth by playing the role of "early adopter," and by creating policies that stimulate the market. As markets are established this leads to Phase III, Expansion of Markets and Infrastructure. The start of Phase III is consistent with a positive commercial decision for vehicles in 2015. A positive decision will attract investment in infrastructure for fuel cell manufacturing, and for hydrogen production and delivery. Government policies still may be required to nurture this infrastructure expansion phase.

Phase IV, which should begin about 2025, is Realization of the Hydrogen Vision, when consumer requirements will be met or exceeded; national benefits in terms of energy security and improved environmental quality are being achieved; and industry can receive adequate return on investment and compete globally. Phase IV provides the transition to a full hydrogen economy by 2040.

Budget Outlook

The Administration's FY 2004 Budget puts the program on track to meet the 2015 milestones. The Office of Energy Efficiency and Renewable Energy's (EERE) budget request of $256.6 million to support the President's FreedomCAR partnership and the Hydrogen Fuel Initiative breaks out as follows:

Hybrid Vehicle Technologies	$91.1 million
Fuel Cells	$77.5 million
Hydrogen	$88 million

Note that there is an additional $16.2 million requested by the DOE Offices of Fossil Energy ($11.5 million) and Nuclear Energy ($4 million), and the Department of Transportation ($0.7 million), for hydrogen production and delivery activities. Additionally, there is $47 million requested in DOE's Office of Fossil Energy for crosscutting fuel cell systems and related technical issues.

The President outlined $1.2 billion over the next five years for hydrogen and fuel cells to advance a commercialization decision by 15 years, from approximately 2030 to 2015. This does not include amounts for carbon sequestration under the FutureGEN and related activities, nor does it include ongoing hydrogen and fuel cell R&D at other federal agencies (except for a subset of DOT spending). While the bulk of the effort will be within my office, the DOE Offices of Fossil Energy and Nuclear Energy, and the Department of Transportation will undertake significant efforts. In addition, we will work with the DOE Office of Science to explore how fundamental science can be applied to solve hydrogen and fuel cell barriers, and will coordinate our infrastructure work with DOT.

Conclusion

Mr. Chairman, it will take a great deal to achieve this vision of a hydrogen energy future we are all talking about this morning. It will require careful planning and coordination, public education, technology development, and substantial public and private investments. It will require a broad political consensus and a bipartisan approach. Most of all, it will take leadership and resolve.

The President has demonstrated his leadership and resolve. "With a new national commitment," said the President during his State of the Union address, "our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen and pollution free."

A few days later at an event on energy independence featuring new uses for fuel cells including automobiles, the President reiterated his commitment to his new Hydrogen Fuel Initiative stating, "The technology we have just seen is going to be seen on the roads of America. And it's important for our country to understand that by being bold and innovative, we can change the way we do business here in America; we can change our dependence upon foreign sources of energy; we can help with the quality of the air; and we can make a fundamental difference for the future of our children."

We believe that the benefits the President envisions are attainable within our lifetimes and will accrue to posterity, but they will require sustained work and investment of public and private financial resources. We at the Department of Energy welcome the challenge and opportunity to play a vital role in this nation's energy future and to support our national security in such a fundamental way.

This completes my prepared statement. I would be happy to answer any questions you may have, either now or in the future.

Chairman BOEHLERT. Thank you, very much. We will go to Dr. Lloyd. We will have to take a break to respond to the Call of the House. Dr. Lloyd.

STATEMENT OF DR. ALAN C. LLOYD, 2003 CHAIRMAN FOR THE CALIFORNIA FUEL CELL PARTNERSHIP

Dr. LLOYD. Good morning, Mr. Chairman and members of the Committee. My name is Alan Lloyd, and I am Chairman of the California Resources Board, and as you indicated, I am also Chairman of the 2003 of the California Fuel Cell Partnership. My immediate predecessor in that role as Chairman, was in fact Don Huberts from Shell. And also from—to say that the partnership is a voluntary cooperative effort to demonstrate fuel cell vehicles and fuel—vehicle fueling options in a collaborate environment. And I am testifying today on behalf of the Partnership. I would also say that four of the five panelists are, in fact, working in that Partnership.

The Partnership was created in 1999. Eight auto manufacturers, four energy providers, two technology providers, fuel cell companies, six government agencies, and ten associate partners, they are listed in my written testimony. I think the goals of the Partnership to demonstrate fuel cell powered electric vehicles on a day-to-day real-world driving conditions are not just our own. We test a variety of fuels and demonstrate the viability of an alternate fuel infrastructure, exploring the path to commercialization, and the key issue there of increased public awareness of fuel cell electric vehicles.

Our energy members are working through the challenges of developing fuel infrastructure for fuel cell vehicles. Similarly, we are working very closely with the auto members. But given that of the brevity here, I would defer significant comments on infrastructure and the automotive technology there to my colleagues Don Huberts and Dr. Burns.

The members of the Partnership have successfully placed 26 fuel cell vehicles, 23 light duty, and three buses, and seven hydrogen fueling stations in California to day. The challenge that we have encountered have been overcome through the diligent attention of our members to technical success, collaboration, and raising public and stakeholder awareness. The Partnership expects to have up to 60 hydrogen vehicles and at least three additional stations operating in California by the end of 2004.

The challenges to a broader implementation of fuel cell vehicles and fueling are four fold. The technical challenge on the vehicle, cost, both infrastructure and the vehicle expanding infrastructure, and education of the stakeholders. And as I indicated, more details are provided in my written testimony.

The hydrogen fueling stations that have been successfully set in California to date have been a result of Partnership members working closely with local officials, including fire and building departments and hazardous materials officers to make them aware of the properties of hydrogen, general safety precautions, how to respond in an emergency. Once local officials are properly informed, a fueling station can be permitted and cited with full community support.

The other issues relating to product standards, infrastructure expansion, I think is critical to the work in the Partnership here with the Society of Automotive Engineers and others. I would mention as an example as a station which is being used in renewable hydrogen—well not, just renewable hydrogen, this case is one of the transit stations where we have electrolysis of water providing hydrogen for some buses. That is augmented by a station we have with the partnership which uses hydrogen, which is brought in. And that is used at either 3,500 and 5,00 PSI.

The important pieces on education I have indicated in my written testimony. I think public awareness, educating emergency responders, developing student curriculums I think is very, very important.

I think addressing specifically the Bill before you in the Hydrogen Future Act; I think this is a good beginning. I think the commercialization of hydrogen fuel cells is a matter of national security, of which the motivation behind the Hydrogen Future Act. Security of energy supplies economic security, national security, and environmental security. Obviously, these huge stakes require us to be bold, innovative, and courageous.

Our goal of commercializing hydrogen fuel-cell systems for energy supply and for transportation will require great economic change, and also social change. It can only be accomplished by the kind of public/private collaboration of what—in which the Partnership is one example.

The President's recent policy announcement, has given the effort unprecedented momentum. The proposed revisions in of the Matsunaga Act, soon to be the Brown-Walker Act, provide us a framework for such a program. We know all too well how much our security is related to our limited sources.

In respect to funding levels, President Bush has proposed 1.2 billion for fuel cell vehicles and related hydrogen infrastructure for the next five years. Our members have supported this initiative enthusiastically. It provides an authorized level of about 500 million for fuel cells and 700 million for hydrogen between Fiscal Year 2004 and 2008.

I hope the Committee will adjust its authorities in both Title I and Title II. Chairman Boehlert has spoken favorable of the Program. I think this is a chance for the Committee to show its collective support.

The Program outlined by the President for transportation and stationary fuel cell research and development, and hydrogen infrastructure has received the most attention, but achieving a hydrogen economy will require a comprehensive program. The large industry coalition outlined a plan in its document Fuel Cells and Hydrogen Path Forward. The document is consistent with the President's proposal, but identifies additional needs for research and in fuel cells as well as tax incentives, buy-downs, and non-financial incentives to encourage investment in a hydrogen infrastructure and fuel cells.

I think buying and using units may encourage the private sector to buy and use these units is the best way to facilitate the introduction to fuel cells and hydrogen. The Partnership is working together to develop and demonstrate hydrogen fueling infrastructure.

There are technology needs in this area, but also we need sufficient resources to develop, test, and choose the best approaches.

The Committee might want to modify the Bill language to recognize this priority and better focus the government's hydrogen activities.

Similarly, on the fuel cell side, I would like to urge the Committee to give greater emphasis to demonstration for the government facilities and in the private sector. I can not stress that sufficiently because unless you get out there and, so to speak, kick the tires, the public doesn't get comfortable with that. We don't understand some of the issues. And both of these benefits would benefit the kind of integrations and cooperation that the Bill envisions.

I think it is also important that the government give priority or stimuli to uniform and balanced International Standards for health and safety, and for working with industry on international component commercial standards. I note in the Bill we talked about quality measures. We found in the development of electric vehicles in California markets that voluntary consensus was impossible to achieve, for example, vehicle charging techniques.

Speaking as a former Chair of the DOE's Hydrogen Technical Advisor Committee, I——

Chairman BOEHLERT. Dr. Lloyd, could we ask you to wrap it up, we have to respond to the House? Okay, it appears that you and I collaborated on our opening statements, but I can assure the audience the independent thought.

Dr. LLOYD. Okay, how much—how long do I have?

Chairman BOEHLERT. One minute.

Dr. LLOYD. Okay. I think as a member of the Chair—a former Chair of the DOE Technical Advisory Committee, I think it is important that that committee has its resources. I was frustrated when I was Chair that the recommendation of the Panel didn't get to the highest levels of DOE. I have confidence that as outlined here, if that authority is given, then in fact some of the additional Committee's Oversights and generation of reports may not be necessary.

[The prepared statement of Dr. Lloyd follows:]

PREPARED STATEMENT OF ALAN C. LLOYD

Invited Testimony guidelines

The testimony should describe the barriers to a hydrogen economy, and how the California Fuel Cell Partnership (CaFCP) is working to overcome those barriers. In particular, the Committee would like you to answer these questions:

1) What obstacles has the CaFCP faced in putting hydrogen vehicles and infrastructure "on the ground"? How have you overcome these obstacles, and how do you plan to do so in the future?
2) What elements should be included in the Department of Energy's hydrogen program to both effectively develop hydrogen technologies and promote their adoption?
3) What are the greatest hurdles the country will face in converting to a hydrogen economy? To what extent is a federal effort needed to clear the way?

Testimony to the Committee on H.R. 238

Good Morning, Mr. Chairman and Members of the Committee. My name is Alan Lloyd. I am the Chairman of the California Air Resources Board (ARB).

This year, 2003, I am also serving as the Chairman of the California Fuel Cell Partnership (CaFCP), a voluntary, cooperative effort to demonstrate fuel cell vehicles and vehicle fueling options in a collaborative environment. Per your request, I am testifying on behalf of the California Fuel Cell Partnership.

California's active participation and support of the CaFCP is based on the potential of hydrogen fuel cell vehicles to help us attain health related air quality goals, as well as the energy security goals of our state and nation. Fuel cells operate on hydrogen, which can be derived from domestic resources and renewable energy. The only emission from a compressed or liquid hydrogen fuel cell vehicle is water. With the proper level of federal assistance, fuel cells can provide the long-term solution to the Nation's air quality and energy security problems.

The CaFCP was established in April 1999. Its members include:

1. Auto manufacturers
   - DaimlerChrysler
   - Ford
   - GM
   - Honda
   - Hyundai
   - Nissan
   - Toyota
   - Volkswagen
2. Energy providers
   - BP
   - ExxonMobil
   - Shell Hydrogen
   - ChevronTexaco
3. Fuel cell companies
   - Ballard Power Systems
   - UTC Fuel Cells
4. Government agencies
   - California Air Resources Board
   - California Energy Commission
   - South Coast AQMD
   - U.S. Department of Energy
   - U.S. Department of Transportation
   - U.S. Environmental Protection Agency

Ten Associate Partners assist with specific expertise to help meet the Partnership's goals:

1. Hydrogen and fuel station suppliers
   - Air Products and Chemicals, Inc.
   - Praxair
   - Pacific Gas & Electric
   - Proton Energy Systems, Inc.
   - Stuart Energy Systems
   - Z–Tek
2. Methanol fuel supplier
   - Methanex
3. Transit agencies
   - AC Transit, San Francisco Bay area
   - SunLine Transit Agency, Palm Springs area
   - Santa Clara Valley Transportation Authority, San Jose

Former chairs include:

- John Wallace (retired), Ford Motor Co., 2000
- Ferdinand Panik (retired), DaimlerChrysler, 2001
- Don Huberts, Shell Hydrogen, 2002

The goals of the CaFCP are:

1. Demonstrate fuel cell-powered electric vehicles under day-to-day, real world driving conditions
2. Test a variety of fuels and demonstrating the viability of an alternative fuel infrastructure
3. Explore the path to commercialization
4. Increase public awareness of fuel cell electric vehicles

The CaFCP maintains a "fuel neutral" position regarding the choice of feed stock fuel for fuel cell vehicles. It's the common sense thing to do at this stage of exploration, in order to gain insight and experience with all potential fuels. Our Energy members are working through the challenges of developing a fuel infrastructure for fuel cell vehicles. Their efforts include the installation of our "home" hydrogen station in West Sacramento, several small hydrogen stations that use natural gas reformation or electrolysis of water technologies, and a methanol station—methanol is a hydrogen carrier fuel that can be reformed to provide hydrogen. During this early stage, all of the vehicles have been powered by hydrogen. We will also be testing liquid fuels rich in hydrogen—methanol and a cleaner form of gasoline—so that we can learn more and determine what will best serve a successful commercial launch.

The members of the CaFCP have successfully placed 26 fuel cell vehicles (23 light-duty vehicles and 3 buses) and 7 hydrogen fueling stations (West Sacramento, Richmond, Irvine, Palm Springs area, Los Angeles, Torrance—Honda and Toyota) in California to date. The challenges that we have encountered have been overcome through the diligent attention of our members to technical success, collaboration and raising public and stakeholder awareness. The CaFCP members expect to have 60 hydrogen fuel cell vehicles and at least 3 additional hydrogen stations (Davis, Auburn and LAX) operating in California by the end of 2003. In 2004, our transit agency associate partners will begin operation of seven 40-foot fuel cell buses.

We believe we have made a great beginning. With additional pilot fleet demonstrations that will prepare markets for a nationwide transition, we are hopeful that we can help achieve the dream of an energy future based on hydrogen.

[What obstacles has the CaFCP faced in putting hydrogen vehicles and infrastructure "on the ground"? How have you overcome these obstacles, and how do you plan to do so in the future?]

The challenges to a broader implementation of fuel cell vehicles and fueling are four-fold: vehicle technical challenges, cost, expanding the fueling infrastructure and education of stakeholders.

Vehicle technologies

The auto companies are addressing a number of challenges including onboard hydrogen storage, all-weather start-up and durability. I won't speak to these in detail, but suffice it to say that the vehicles being tested in California, while vastly improved over the versions available only a couple of years ago, are still early prototype or very limited production vehicles for early fleet trials. The good news is that all of the auto companies are confident and diligently working to resolve the remaining technical challenges.

Cost

The cost of fuel cell technology needs to come down. Fuel cells and fuel cell vehicles are hand built today at great cost. While General Motors has established a cost target of $500 per kilowatt for fuel cells in stationary power applications in 2005, to be competitive with internal combustion engine vehicles, the cost must be reduced to perhaps $50 per kW. Achieving these cost targets will require advances in materials, manufacturing, and, most importantly, sufficient demand to reduce the cost of components. The CaFCP is not collectively addressing the cost challenge however, each member faces this hurdle everyday.

Infrastructure

A fueling infrastructure for fuel cell vehicles must be established. This provides significant challenges including codes, standards, and expansion strategies.

1. Codes and Standards

Virtually all the auto manufacturers have announced plans to begin vehicle demonstrations using compressed hydrogen fuel rather than producing the hydrogen onboard the vehicle by reforming another fuel. Providing hydrogen for consumers will require significant investment, massive public education, and modification of health and safety codes and recommended practices. Current codes and standards for hydrogen were not written with vehicle fueling in mind.

The hydrogen fueling stations that have been successfully sited in California to date have been the result of CaFCP members working closely with local officials, including fire and building departments and hazardous materials officers, to make them aware of the properties of hydrogen, general safety precautions and how to respond in an emergency. Once local officials are properly informed, fueling stations can be permitted and sited with full community support.

Regarding codes and standards pertaining to facility designs, we successfully permitted a unique headquarters facility in West Sacramento more than two years ago. The 55,000 square foot building houses hydrogen-safe work bays for the auto partners and Ballard, office space for CaFCP personnel, and has hydrogen and methanol fueling station on-site. We learned a lot in that process, and now are conducting a study with an engineering design firm to determine how such facilities, as well as parking structures and home garages, should be designed to accommodate hydrogen-fueled vehicles in the future. The goal is to ensure safety while minimizing the modifications and costs needed.

As we move forward to install a broader fueling infrastructure, uniform national and state codes and will be important to streamline the siting and permitting process—and to allow fueling stations to be sited as commercial establishments. For example, the West Sacramento hydrogen station was required to be placed 75 feet from the headquarters building. Fortunately, there was enough space to accommodate the distance but this space requirement would prohibit hydrogen fueling stations in a commercial setting. Several of the CaFCP members are participating in code setting organizations such as the International Code Council (ICC) and National Fire Protection Agency (NFPA) to this end.

2. Product Standards

A related area is component standards or recommended practices. Another challenge that was addressed by the CaFCP members was the lack of commonality of hydrogen refueling nozzles. The CaFCP members worked with the Society of Automotive Engineers (SAE) to give feedback for establishing a common standard for hydrogen fueling nozzles. In addition we have collected real-world data on hydrogen fueling of the vehicles and provided that to SAE. That same data was later utilized by SAE to improve upon the standard (pressurized) tank design used in natural gas vehicles to accommodate hydrogen in fuel cell vehicles.

3. Infrastructure expansion

In order to expand the range of the hydrogen fuel cell vehicles, we are faced with the challenge of increasing the hydrogen fueling infrastructure. The CaFCP operates a "home base" fuel station at our headquarters in West Sacramento which is supplied with liquid hydrogen by Air Products & Chemicals and Praxair. Small stations are being placed throughout California to increase the distance a hydrogen vehicle can travel from "home." We believe that these stations will create a network so that fuel cell vehicles will be able to move throughout California.

An example of one such station is the CaFCP hydrogen satellite station—approximately 70 miles southwest of Sacramento at the Richmond Operating Division of AC Transit. The Stuart Energy appliance technology uses water electrolysis to generate hydrogen fuel on-site for vehicles. The advantages of the distributed hydrogen generation system is that it is convenient, easy to install and available immediately. The station is capable of supplying the fueling needs of a small fleet of vehicles on a daily basis. The entire integrated station consists of a high-pressure, high-purity hydrogen generator, a storage unit, and a hydrogen fuel dispenser that resembles a common gasoline dispenser. To fuel a vehicle, the driver simply swipes a "smart" card to activate the dispenser and attaches the nozzle to their vehicle's tank. The computer controls the amount and pressure of hydrogen that is dispensed and automatically shuts off when the tank is full. The entire procedure closely resembles today's consumer fueling procedure.

Setting up a network of fueling stations dedicated to compressed hydrogen for fuel cell vehicles creates a stranded investment risk for developers. One of the CaFCP members, SCAQMD, has a plan to mitigate some of the risk by equipping new CNG stations with subsystems that are capable of dispensing hydrogen. The result will be a network of 10 to 12 stations with the potential to refuel hydrogen. When fuel cell vehicles are introduced into nearby fleets in the 2004 to 2007 timeframe, these stations can then be geared up for actual hydrogen refueling with the addition of a compressor specifically designed for hydrogen.

The CaFCP bus program is being used to expand the hydrogen network for the CaFCP vehicles and educate the public on the safety and reliability of fuel cell vehicles. SunLine Transit Agency demonstrated the Ballard ZEbus (Zero Emission bus) hydrogen fuel cell bus for one year and currently operates a second fuel cell bus in regular fare service. The buses have provided officials and riders alike with an opportunity to experience the pollution-free transportation technology of the future and drew visitors from around the world. Since April 2000, SunLine has generated hydrogen on site from two sources—solar power and natural gas.

Education

The CaFCP and its members have placed a strong emphasis on raising awareness of fuel cell vehicles and fueling. Education is the key to acceptance of hydrogen fuel by the public, the government and industry. Our focus has been in three main areas: the public, stakeholders, and students.

1. Public awareness

Awareness of fuel cells is growing. According to a recent survey conducted for CaFCP, a growing number of Californians look with favor on the development of fuel cell vehicles. Notably, the public by a wide margin approves of government support for pre-commercial demonstration of fuel cell technology and the development of alternative fueling stations. The CaFCP program reached 200,000 people in 2002. The three-day Central Coast Road Rally allowed 100,000 people to get close to the vehicles; to date, 7,000 riders/drivers have personally driven in FCVs fueled with hydrogen at CaFCP events.

2. Emergency responders training

Emergency responders are one of the first groups which the CaFCP has focused its education efforts. CaFCP created an Emergency Response (ER) guide for hydrogen fuel cell vehicles to supplement the U.S. DOT ER guide that does not contain hydrogen vehicle information. In addition the CaFCP has created a training program to educate first responders on general hydrogen safety as well as detailed hydrogen vehicle information, critical to safety in case of an accident. Last year we trained 35 responders representing 5 local agencies in the Richmond area (the location of our hydrogen satellite station). The feedback from the trained responders was that they believed the information to be critical to address this new technology. This year we plan to train 300 first responders located in areas where the fuel cell vehicle fleets will be located (10 agencies in the LA and San Francisco Bay regions).

3. Student curriculums

An educational challenge facing California and the Nation is having enough qualified researchers and trained technicians. The CaFCP is working to create excitement among our next generation of drivers with science competitions and by provides learning kits to help middle and high school teachers find the best resources—including classroom curricula—for introducing to students the scientific principles of fuel cells and their fuels. SunLine Transit Agency and AC Transit have incorporated fuel cell technology into their apprenticeship training programs for heavy-duty vehicle mechanics. SunLine has also worked with the College of the Desert to design a curriculum to train future technicians in an alternative-fuel technology program. The curriculum is posted on the NREL AFDC website.[1]

[What elements should be included in the Department of Energy's hydrogen program to both effectively develop hydrogen technologies and promote their adoption?]

The Committee has before it H.R. 238, which includes revisions to the Hydrogen Future Act. This is a good beginning. The commercialization of hydrogen and fuel cells is a matter of national security, the motivation behind the Hydrogen Future Act:

- Security of energy supply, since hydrogen can be made from abundant domestic sources;
- Economic security, since every million barrels of oil we import each day at $30 per barrel costs us $10 billion a year, not to mention the cost of securing those supplies;
- National security, since a hydrogen future would reduce or eliminate oil-related international tensions and provide a mechanism for more equitably sharing the benefits of access to energy among all nations;
- Environmental security, since fuel cell systems running on hydrogen reduce and can even eliminate conventional pollutants and net greenhouse gases.

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[1] http://www.ott.doe.gov/educational_tools.shtml

These huge stakes require us to be bold, innovative and courageous. Our goal of commercializing hydrogen and fuel cell systems for energy supply and for transportation will require great economic change, and also social change. It can only be accomplished by the kind of public-private collaboration of which the CaFCP is only one example.

The President's recent policy announcements have given the effort unprecedented momentum. The proposed revisions of the Matsunaga Act—soon to be the Brown-Walker Act—provide us a framework for such a program. But I would urge the Committee to take the opportunity to add to the structure, to be bold, while the opportunity is ripe.

In fairness, the authorities in the Matsunaga Act expired in 2001, and thus the programs embodied in Brown-Walker were developed several years ago. We know all too painfully how much our nation has changed since then. We know all to well how much our security is related to oil and its sources. Therefore, even though the Committee's markup schedule is ambitious, I would urge you consider the following changes.

1. Funding levels.
    a. President Bush has proposed 1.2 billion for fuel cell vehicles and related hydrogen infrastructure over the next five years. Our members have supported this initiative enthusiastically. It implies an authorized level of about $500 million for fuel cells and $700 million for hydrogen between FY 2004 and FY 2008. I hope the Committee will adjust its authorities in both Title I and Title II. Chairman Boehlert has spoken favorably of the program; this is a chance for the Committee to show its collective support.
    b. The program outlined by the president for transportation and stationary fuel cell research and development and hydrogen infrastructure has received the most attention, but achieving a hydrogen economy will require a comprehensive program. A large industry coalition has outlined a comprehensive plan in its document, *Fuel Cells and Hydrogen: The Path Forward.*[2] That document is consistent with the President's proposal but identifies additional needs for research in high-temperature fuel cells, as well as tax incentives, buy downs and non-financial incentives to encourage investment in a hydrogen infrastructure and fuel cells. In conjunction with the President's $1.2 billion, these programs if fully authorized would total $2.5 billion over five years overall, a level comparable to the authorization in H.R. 238 for other mainstream energy research programs.
2. Program Focus. *Buying and using units, and encouraging the private sector to buy and use units, is the best way to facilitate the transition to fuel cells and hydrogen.*
    a. The members of the CaFCP are working together to develop and demonstrate a hydrogen fueling infrastructure. There are technology needs in this area, but also we need sufficient resources to develop, test and choose the best approaches. The Committee might wish to modify the bill language to recognize this priority and to better focus the government's hydrogen activities.
    b. Similarly, on the fuel cell vehicle side, I would like to urge the Committee to give greater emphasis to demonstrations, both at government facilities and in the private sector. Both these activities would benefit from the kind of interagency cooperation that the bill envisions; interagency programs would also help expand the type and range of vehicles in use beyond passenger cars. Now is not the time to limit our options.
    c. It is also very important that the government give priority to stimulating uniform and balanced international standards, for health and safety, and work with industry on international component and commercial standards. We found in the development of electric vehicles for California markets that voluntary consensus was impossible to achieve in, for example, vehicle charging techniques.
3. Other areas.

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[2] *Fuel Cells and Hydrogen: The Path Forward,* B. Rose, February, 2003. Available online at: www.fuelcellpath.org

a. Speaking as a former chair of the Hydrogen Technology Advisory Committee, I was pleased to see it reauthorized.
    i. I would caution that it needs resources to do its job.
    ii. My greatest frustration, however, was that its recommendations received insufficient attention from the U.S. DOE.
    iii. The pending bill does have a mechanism for assuring that the recommendations at least are read, but that mechanism will need to be enforced.
    iv. With a strong and visible HTAP, there would be no need in my opinion for additional National Academy of Sciences review nor for at least some of the reports and analyses required of the Secretary.

b. Cost share is often extremely difficult for entrepreneurs.
    i. The cost share waiver language in the bill is a good start at addressing this problem. The Committee may wish to allow the Secretary to waive the cost share not only for high risk programs, but also for extraordinarily high reward programs.
    ii. I might also suggest the Committee consider a small "Innovation Fund" along the lines of the SBIR program, though perhaps with a higher program cost limit.

c. I would be remiss if I did not also encourage the Committee to include enhanced air quality as one of the stated goals of this program. A healthful environment is a national consensus goal and a matter of national security.

[What are the greatest hurdles the country will face in converting to a hydrogen economy? To what extent is a federal effort needed to clear the way?]

The Federal Government will play a critical role in converting the United States into a hydrogen economy. Only an active partnership among the Federal Government, states, private industry and, ultimately, the public, can marshal the financial and human resources to do the job. The goals of the Federal Government's hydrogen and fuel cell vehicle programs should include reducing the cost of hydrogen generation and storage and providing purchase incentives for other public and private entities that want to be early adopters of this technology.

Cost reduction of hydrogen generation and storage

A successful hydrogen economy will require efficient and cost-effective hydrogen production and storage technologies. The CaFCP is investigating different hydrogen production technologies at satellite stations provided by the associate partners. Stuart Energy and Proton Energy Systems manufacture electrolyzers that use water and electricity to produce hydrogen. PG&E and Z–Tek reform hydrocarbon fuels to release their hydrogen content. The issue of hydrogen production is not only being examined in the United States. The Clean Urban Transportation in Europe (CUTE) fuel cell bus program consists of 3 buses in each of 10 cities. Each project will produce hydrogen fuel by a technique that makes sense for the area that the project is located. The hydrogen will be produced from sources ranging from biomass to hydrocarbon fuels. Some of the hydrogen production techniques that produce the least emissions are the most economically challenged. The Federal Government is the only stakeholder that can sponsor the research and development necessary to reduce the cost of these clean technologies and get them into the market.

The Federal Government's hydrogen program must focus on finding better ways to store hydrogen that will allow fuel cell vehicles to drive greater distances on a single fueling. Consumers demand a driving range that is currently not possible with the present, feasible, hydrogen storage onboard vehicles. Auto manufacturers need lightweight, high capacity, and affordable hydrogen storage to make fuel cell vehicles successful in the marketplace. This is one of the biggest challenges to the commercialization of hydrogen fuel cell vehicles and should not be underestimated or under funded.

Support for demonstrations (early adopters)

The Federal Government has the ability to stimulate the early market for hydrogen as a transportation fuel by promoting hydrogen fuel cell vehicles for government fleets and providing early buy-downs for public fleets. While we believe the Partnership is the leading test effort in the world for fuel cell vehicles and hydrogen, California recognizes that a commercial strategy must of course be national. Therefore, additional pilot fleet demonstrations are necessary and the federal program should be national in scope.

The CaFCP sponsored a study that was completed in 2001 to examine the commercialization process for fuel cell vehicles using different fuels—hydrogen was one of the scenario studies.[3] The process for commercialization (no matter the fuel) includes a demonstration phase, a pilot phase, a decision to commercialize, and mass production. Fuel cell vehicles are emerging from the demonstration phase and must be placed in pilot fleets in order to continue down the path of commercialization.

Two CaFCP members, Honda and Toyota, have already placed vehicles into government and university fleets in California. Several other auto members have expressed a desire to place fuel cell vehicles in fleets. The numbers of vehicles are small and the states need close cooperation and support from the Federal Government in order to place significant numbers of vehicles.

For example, the U.S. DOT played a key role in placing orders for seven fuel cell buses that will arrive in California next year by assisting in the attainment of federal funds. The State of California, like many states, does not have the financial resources to support these very expensive pilot programs without federal assistance. Our transit bus demonstration program has been funded by over $16 million in local and state grants, but will need more federal funding to sustain the demonstration and evaluation periods beyond 2006. Fuel cell transit buses have the potential to become commercial in the next ten years. However, the initial buses are expensive and may not have the reliability of everyday buses. We project that we will need another generation of fuel cell bus demonstrations with improved fuel cells and more efficient packages. I believe there is a significant value to the Federal Government sharing the cost burden and gaining experience in California that can be shared in other states to maximize the payoff of every demonstration program dollar. I would like to urge the Committee to support—to the extent of its jurisdiction—multi-year funding under U.S. DOT for ongoing development of fuel cell bus programs as outlined in the National Fuel Cell Bus Technology Program initiative.

Speaking as a member of the CaFCP, the State of California, our biggest challenge is placing significant numbers of hydrogen fuel cell vehicles within the State. The numbers of vehicles that we expect within the next five years do not warrant a significant increase in the capacity of the hydrogen fuel infrastructure that is not already planned. I believe it is of paramount importance for the State to work closely with U.S. DOT for hydrogen fuel cell buses, U.S. DOE and U.S. Department of Defense for hydrogen fuel cell vehicles and U.S. EPA to certify the vehicles in order to be placed in fleets. The U.S., not just California, is competing with Europe and Asia (particularly Japan) for the limited numbers of hydrogen fuel cell vehicles that the auto companies have the resources to provide in the early years. Presently, the only hydrogen fuel cell vehicle that has gone through the full development process, certification, and is built on line at a small volume factory is Honda's FCX. I congratulate Honda and admire the leadership they have shown.

Conclusion

We must be dedicated in our efforts today to make hydrogen our fuel for tomorrow. It will take sustained cooperation between government agencies, industry leaders and nations on the leading edge of new technologies. Many challenges must be addressed but there are none that cannot be overcome. The ARB is participating in the CaFCP to ensure that the State of California takes advantage of every opportunity to accelerate a conversion to a hydrogen future. We cannot succeed without the support of the Federal Government.

I appreciate the opportunity to testify today and urge you to do all that the Federal Government can to make the future fuel—hydrogen, the fuel of today. Thank you for your time and attention.

BIOGRAPHY FOR ALAN C. LLOYD

Alan C. Lloyd, Ph.D., was appointed as Chairman to the California Air Resources Board by Governor Gray Davis in February 1999.

The Air Resources Board (Board), a branch of the California Environmental Protection Agency, oversees a $150 million budget and a staff of nearly 1,100 employees located in northern and southern California. The Board consists of eleven members appointed by the Governor with the consent of the Senate. All members serve "at

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[3] Bringing Fuel Cell Vehicles to Market: Scenarios and Challenges with Fuel Alternatives, Bevilacqua-Kinght, Inc., October, 2001. Available online at: http://www.cafcp.org/event—roundtable.html

the pleasure of the Governor" on a part-time basis, except the Chairman, who serves full-time.

The Board's mission is to promote and protect public health, welfare and ecological resources through effective reduction of air pollutants while recognizing and considering effects on the economy. The Board oversees all air pollution control efforts in California to attain and maintain health-based air quality standards. In addition, the Board gives financial and technical help to 35 local districts establishing controls on industrial emissions. The Board is also responsible for the control of motor vehicle and consumer products air pollution, and the identification and control of toxic air contaminants.

Dr. Lloyd most recently served as the Executive Director of the Energy and Environmental Engineering Center for the Desert Research Institute at the University and Community College System of Nevada, Reno. Previously, Dr. Lloyd was the chief scientist at the South Coast Air Quality Management District from 1988 to 1996, where he managed the Technology Advancement office that funded public-private partnerships to stimulate advanced technologies and cleaner fuels.

As Chairman, Dr. Lloyd is committed to cultivate a mindset and an attitude throughout government, industry and society that zero- and near-zero emission technologies can be put to use now or in the immediate future to help the state meet its air quality goals. He initiated the environmental justice focus within the agency and led the efforts resulting in the adoption of the Environmental Justice Policy and actions to be followed up by the Board.

Dr. Lloyd has given many presentations to national and international audiences, focusing on the viable future of advanced technology and renewable fuels, with attention to the urban air quality challenges faced by California and to the impact on global climate change. He is a major proponent of alternate fuels, electric drive and fuel cell vehicles eventually leading to a hydrogen economy. Dr. Lloyd has also authored many articles on alternative fuels and air pollution control technology, including *Fuel Cells and Air Quality: A California Perspective; Electric Vehicles and Future Air Quality in Los Angeles; Air Quality Management in Los Angeles: Perspectives on Past and Future Emission Control Strategies;* and *Accelerating Mobile Source Emission Reductions: California's Experience and Recommendations to Developing Counties.*

Dr. Lloyd is the 2003 Chairman of the California Fuel Cell Partnership and is a co-founder of the California Stationary Fuel Cell collaborative. He is a past chairman of the U.S. Department of Energy Hydrogen Technical Advisory Panel (HTAP).

Dr. Lloyd, 61, earned both his Bachelor of Science in Chemistry and Ph.D. in Gas Kinetics at the University College of Wales, Aberystwyth, U.K.

Chairman BOEHLERT. Thank you very much, Dr. Lloyd.

Dr. LLOYD. Thank you.

Chairman BOEHLERT. We must go now. We will recess for approximately 15 minutes, and during that period you can confer with the high-level DOE Official to your right.

[Recess]

Chairman BOEHLERT. Before we start, I ask unanimous consent of a former colleague of ours, Dick Chrysler of Michigan be permitted to sit on the dais, not to ask any questions but to observe. And he doesn't have any special interest in this other than as a citizen. Mr. Chrysler, you are welcome to take a seat up here. And we will resume. Dr. Ogden, you are up. And then speak closely.

STATEMENT OF DR. JOAN M. OGDEN, RESEARCH SCIENTIST, PRINCETON ENVIRONMENTAL INSTITUTE

Dr. OGDEN. Let us see, I guess the screen is up there. Well, good morning. It is a real pleasure to be here. My name is Joan Ogden. I am a research scientist at Princeton University, with a background in physics, and for the last, approximately, 15 years; I have conducted a number of technical and economic assessments of hydrogen and fuel cell energy systems. So today I am going to talk to you a little about what I see the prospects for large scale use of hydrogen in the future energy system.

PROSPECTS FOR LARGE-SCALE USE OF HYDROGEN IN OUR FUTURE ENERGY SYSTEM

Joan M. Ogden, Ph.D.

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Testimony to the Committee on Science
United States House of Representatives
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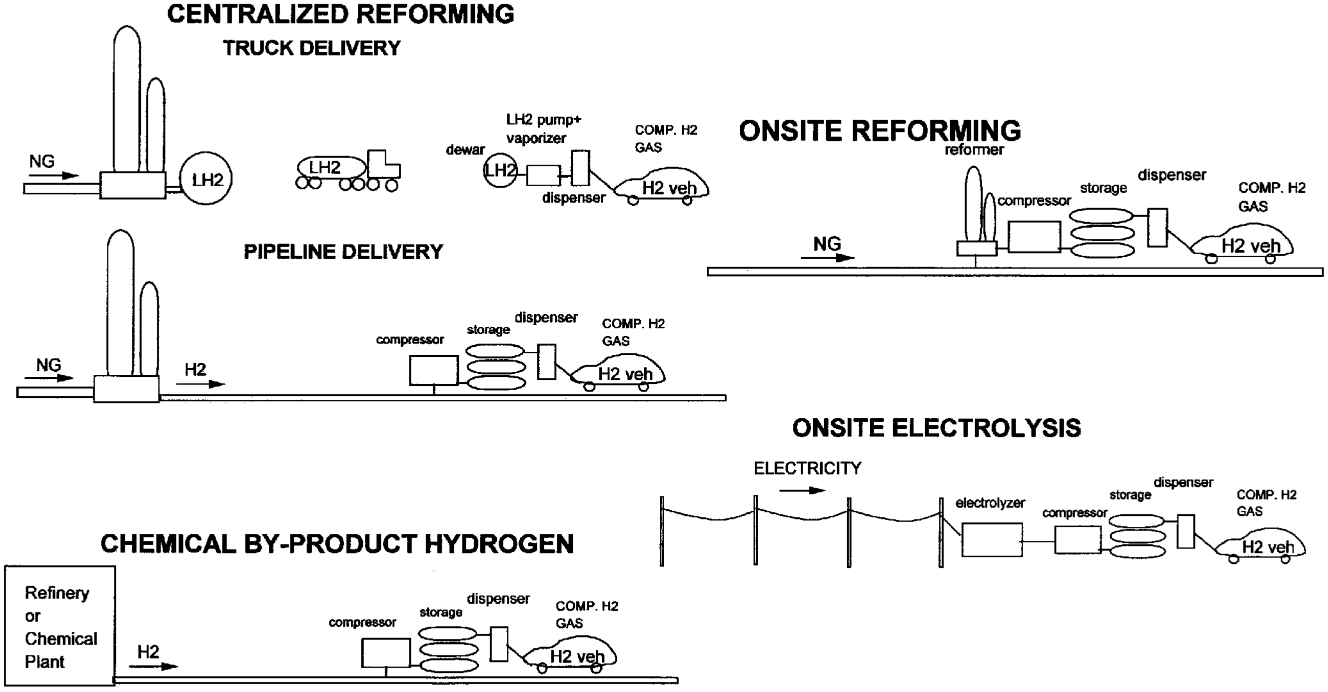
OPTIONS FOR H_2 PRODUCTION AND DELIVERY

- Hydrogen is widely used in chemical and refining industries today. About 1% of US energy use goes to make hydrogen.
- Technologies for large scale H_2 production, storage, and delivery by truck or pipeline are in commercial use. The “merchant hydrogen” infrastructure delivers enough hydrogen to fuel ~1% of US cars (if they used H_2 fuel cells). These technologies are being adapted for H_2 energy systems.
- Most H_2 is made from natural gas today. There are a number of options for producing and delivering H_2 that use commercial or near-commercial technologies. In the longer term H_2 could be made from fossil fuels (coal), renewables (biomass, wind, solar) or nuclear power. H_2 costs more than current gasoline per unit of energy, but can be used more efficiently.

NEAR TERM H_2 SUPPLY OPTIONS



CENTRALIZED REFORMING

TRUCK DELIVERY

PIPELINE DELIVERY

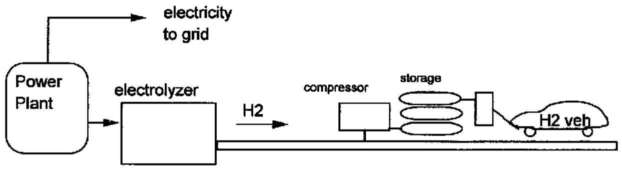
ONSITE REFORMING

ONSITE ELECTROLYSIS

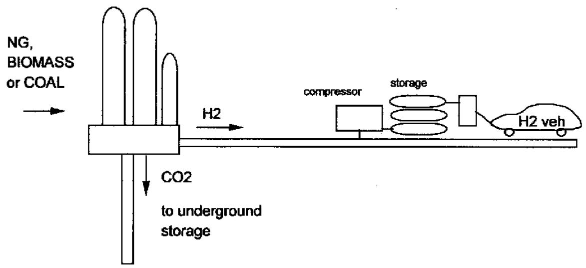
CHEMICAL BY-PRODUCT HYDROGEN

LONG TERM H_2 SUPPLY OPTIONS

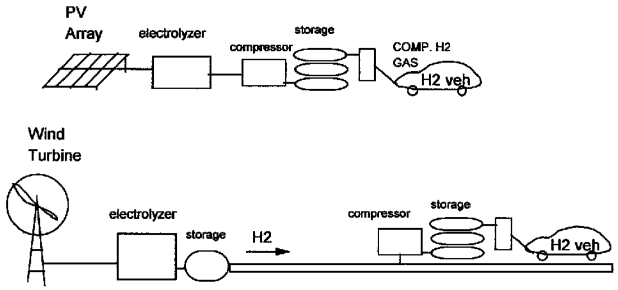
CENTRALIZED PRODUCTION OF ELECTROLYTIC H2



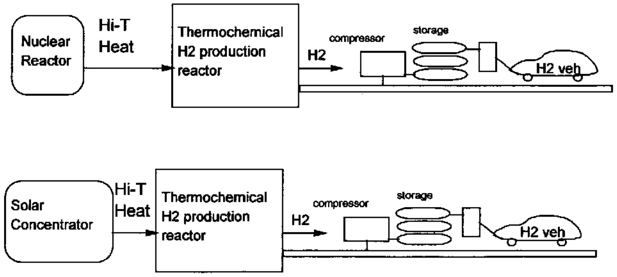
H2 FROM HYDROCARBONS w/CO2 SEQUESTRATION



SOLAR or WIND ELECTROLYTIC H2



H2 PRODUCTION VIA THERMOCHEMICAL CYCLES POWERED BY NUCLEAR OR SOLAR HEAT

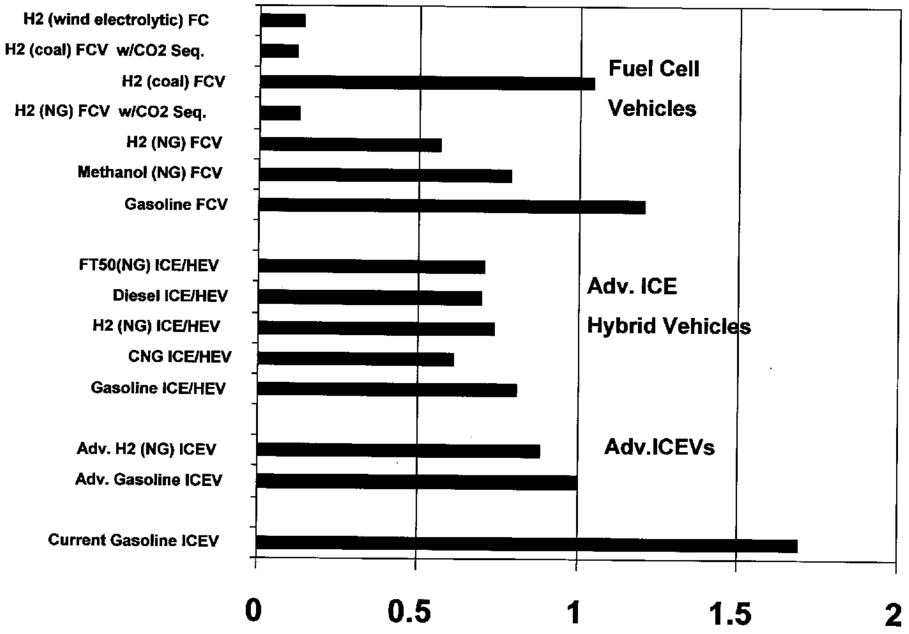


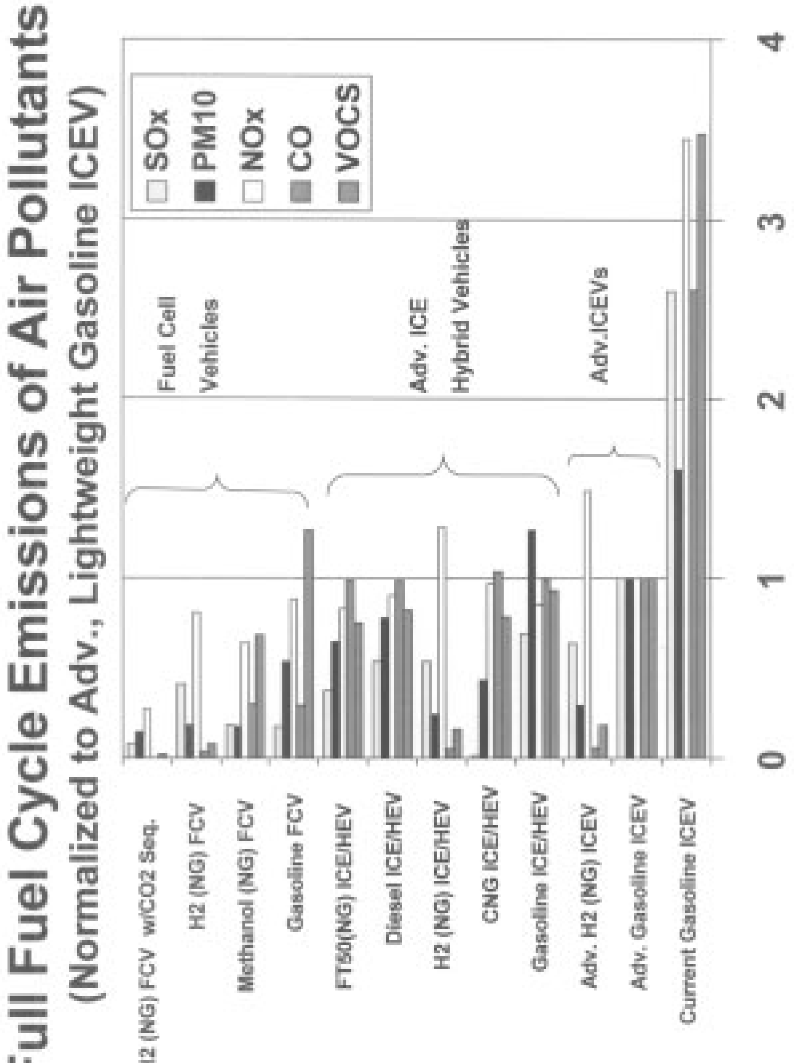
USING H_2 IN VEHICLES CAN REDUCE EMISSIONS AND OIL CONSUMPTION COMPARED TO CONVENTIONAL FUELS

Fuel cell vehicles using H_2 from decarbonized fossil, renewable or nuclear sources could have near zero emissions of greenhouse gases and air pollutants "well to wheels"

FULL FUEL CYCLE GREENHOUSE GAS EMISSIONS

(Normalized to Adv. Lightweight 46 mpg Gasoline ICEV)




Full Fuel Cycle Emissions of Air Pollutants
(Normalized to Adv., Lightweight Gasoline ICEV)
SOx
PM10
NOx
CO
VOCS
Fuel Cell Vehicles
Adv. ICE Hybrid Vehicles
Adv.ICEVs
H2 (NG) FCV w/CO2 Seq.
H2 (NG) FCV
Methanol (NG) FCV
Gasoline FCV
FT50(NG) ICE/HEV
Diesel ICE/HEV
H2 (NG) ICE/HEV
CNG ICE/HEV
Gasoline ICE/HEV
Adv. H2 (NG) ICEV
Adv. Gasoline ICEV
Current Gasoline ICEV
0
1
2
3
4

EXTERNALITIES COULD BECOME AN IMPORTANT DRIVER FOR H_2

- It is highly uncertain today what economic values should be assigned to external costs of energy (climate change, health effects from air pollution, oil supply insecurity).
- H_2 FCVs have the lowest overall externality costs of any option.
- At mid-range valuations of external costs, H_2 FCVs are lifecycle cost (LCC)competitive with other advanced vehicle options, if externality costs are included. At the high end of the range of externality costs, H_2 FCVs have lowest lifecycle cost.

BARRIERS TO A HYDROGEN ECONOMY

- current high cost of H_2 end-use technologies
- current lack of a H_2 infrastructure
- technologies better adapted for a H_2 energy economy could speed progress (e.g. onboard H_2 storage, small scale H_2 production systems, fossil H_2 production with CO_2 sequestration) .
- lack of policies reflecting the external costs of energy

POLICIES WILL PROBABLY BE REQUIRED TO BRING ABOUT A H_2 ECONOMY, INCLUDING VALUATION OF EXTERNALITIES

In world where H_2 is widely used externalities will be more important than they are now. Political will and markets will evolve together, reflecting profound changes in how we view energy as a society.

Factors that could accelerate adoption of H_2 : 1) technical breakthroughs, and 2) potential market pull of fundamentally new products and services enabled by the use of H_2 or fuel cells.

POLICIES TO ENCOURAGE USE OF H_2

- R&D on key concepts, where a breakthrough could speed the adoption of H_2 (e.g. H_2 storage, small scale H_2 production, CO_2 sequestration)
- Demonstration of H_2 production and end-use technologies.
- Policies to encourage “buy-down” of H_2 technologies such as fuel cells. For example, use of H_2 in ZEV fleets.
- Policies to value externalities: air pollution standards, feebates for clean efficient vehicles, fuel economy standards, gasoline tax, carbon tax

EVEN UNDER OPTIMISTIC SCENARIOS, IT WILL TAKE SEVERAL DECADES BEFORE H_2 CAN IMPACT EMISSIONS ON A GLOBAL SCALE

It is important to encourage use of efficient gasoline internal combustion engine vehicles now, to address the environmental and energy supply security problems now, while we are developing H_2 and fuel cells.

CONCLUSION

- Should long-term concepts like hydrogen and fuel-cell vehicles have high priority, given that relatively modest improvements in more traditional internal combustion engine technologies could help address environmental and energy supply problems much sooner? In my view, hydrogen and fuel-cell technologies, although high-risk and long-term, have a potentially very high payoff. Therefore, they deserve significant government support now, as “insurance,” so that they will be ready in 15-20 years, if and when we need to deploy them widely.

- I would encourage a comprehensive strategy, based on developing and encouraging the use of clean, efficient internal combustion engine vehicles in the near term, coupled with a longer term strategy of research, development and demonstration of hydrogen and fuel cells. Consistent policies to encourage use of cleaner transportation systems with lower carbon emissions and to move away from our almost exclusive dependence on crude oil-derived transportation fuels would encourage adoption of advanced internal combustion engine vehicles in the near term and, eventually, of hydrogen vehicles.

Could you click that for me Larry, please, the next one? Thank you. First I am going to just mention a little about different options for producing hydrogen and delivering it. Hydrogen is actually widely used in the chemical and oil refining industries today, and about one percent of U.S. energy, and five percent of our natural gas use goes to making hydrogen. As you might expect, technologies for high scale hydrogen production, storage, and delivery by truck and pipeline are in commercial use today. And the merchant high in infrastructure delivers enough hydrogen by truck and pipeline to fuel perhaps one percent of U.S. cars, if they were all run on efficient fuel cell vehicles or hydrogen vehicles.

Current hydrogen technologies are now being developed for use in energy systems. Most of the hydrogen is made from natural gas today, but there are a number of options for producing and delivering hydrogen. Dr. Garman mentioned these, most of them could be implemented using commercial or near commercial technology. In the longer term, you could make hydrogen from fossil fuel, such as natural gas or coal, possibly with the capture and sequestration of CO_2, so it doesn't go into the atmosphere, renewables, such as bio-mass. That would energy crops or wastes, wind, solar, or nuclear power. Hydrogen would cost more than current gasoline, but you could use it more efficiently.

In your testimony, there are a couple of figures that show a number of different hydrogen production options. I just might mention of the ones shown in that written testimony of probably the nuclear term of chemical are not as far along. That is really in the laboratory stage. Most of the others are based on commercial or near-term technology.

Using hydrogen in vehicles can reduce emissions and oil consumption compared to the conventional fuels. And I won't go on about this because it is very nicely shown in the graphs by Dr. Garman. But I might say that hydrogen vehicles using hydrogen from renewable, de-carbonized fossil or nuclear sources could have near zero emissions of greenhouse gases and air pollutants on a well-to-wheels basis. That is all the emissions involved in extracting the feedstock, producing hydrogen and using it.

Externalities we think could become an important driver for hydrogen in the future. It is uncertain today what exact value you should assign to the cost of things like global warning, but hydrogen vehicles can offer what appear to be the lowest overall externalities cost of any option, and we think this may make it—help make it very competitive in the future.

One of the barriers to a hydrogen economy, the current lack of a hydrogen infrastructure; unlike gasoline or natural gas, hydrogen is not delivered to consumers today. It is not so much a matter of the technology breakthrough being needed to do it; it is more of a matter of matching supply and demand as the system grows in a cost-effective way. Currently hydrogen end-use technologies like fuel cells costs a lot. Some of the technologies could be more mature, let us say, adapting existing hydrogen technologies for a hydrogen energy economies could speed progress, particularly in areas like hydrogen storage onboard vehicles, small scale hydrogen production systems for use in refueling stations, and for fossil-hydrogen as a long-term option, CO_2 sequestration.

And finally, I would say there is a lack of policies of reflecting the external cost of energy presently. I think that policies would probably be required to bring about a hydrogen economy, including evaluation of externalities. Let me rather rephrase that to say I see a world where hydrogen is widely used as one where externalities be much more important than they are now. I think it will involve a real paradigm shift. I would see political will and policies in markets sort of evolving together, reflecting a profound change in how we view energy as a society.

And we have begun to debate on that now, which I am very glad to see. I think it is a process that will take place over time. Certainly there are factors that could accelerate the adoption of hydrogen, with technical breakthroughs and things like storage that might make it easier to handle hydrogen and potential market pull of fundamentally new products and services that could be enabled by hydrogen in fuel cells. And I expect some of the other folks on the panel will talk some about those.

Policies that might encourage use of hydrogen, the first couple of these are already happening, R&D on key concepts. The R&D programs are certainly addressing some of these; demonstration of hydrogen production infrastructure in end-use technologies through efforts like the California Fuel Cell Partnership. They also say there could be arousal for policies to encourage buy-down of hydrogen technology such as fuel cell and infrastructure. And finally, I would say policies to value externalities, emissions standards that be bates any number of things could help encourage the use of hydrogen.

Just to mention, as everyone knows here, hydrogen is a long-term option. We will be in this for the long-haul, even for optimistic scenarios that might take several decades before hydrogen could impact emissions on a global scale. That having said, in the near-term it is important to do what we can now in terms of encouraging more efficient use of fossil resources, and the more efficient eternal combustion engine vehicles to address these while we are developing things like hydrogen and fuel cells, which we are going to need for the longer term.

In conclusion, I just say, hydrogen and fuel cells, although they are long-term, they are potentially a very high pay off, and I think they deserve significant government support now. Insurance, if nothing else, so they will be ready in 15 to 20 years if we want to deploy them on a very wide basis. And I would like to see a comprehensive strategy on policies based on encouraging use of more of clean, efficient technologies available in the near-term, coupled with longer term strategy we seem to be embarking on, which would involve development of hydrogen fuel cells. Thank you.

[The prepared statement of Dr. Ogden follows:]

PREPARED STATEMENT OF JOAN M. OGDEN

INTRODUCTION

Globally, direct combustion of fuels for transportation and heating accounts for about two thirds of greenhouse gas emissions, a significant fraction of air pollutant emissions and about two thirds of primary energy use. Even with continuing incremental progress in energy technologies, most energy forecasts project that primary energy use and emissions of greenhouse gases and air pollutants from use of fuels will grow over the next century, because of increasing demand, especially in developing countries. To stabilize atmospheric CO_2 at levels of 450–550 ppm (a level that climate analysts suggest would avoid undue interference with climate), it will be necessary to significantly reduce carbon emissions from the fuel sector, even if the electric sector completely switches to non-carbon emitting sources by 2100 (Williams, 2003). Energy supply security is a serious concern, particularly for the transportation sector, which depends almost entirely on fuels derived from crude oil.

A variety of alternative fuels have been proposed that could help address future environmental and energy supply challenges. These include reformulated gasoline or diesel, compressed natural gas, methanol, ethanol, synthetic liquids from natural gas or coal such as Fischer-Tropsch liquids or dimethyl ether (DME), and hydrogen. Of these, hydrogen offers the greatest potential environmental and energy supply benefits. Like electricity, hydrogen is a versatile secondary energy carrier that can be made from a variety of widely available primary energy sources including natural gas, coal, biomass (agricultural or forestry residues or energy crops), wastes, solar, wind or nuclear power. Hydrogen can be used with high conversion efficiency and essentially zero emissions. If hydrogen is made from renewable, nuclear or decarbonized fossil sources (e.g., energy production from fossil fuels with capture and secure storage of carbon), it would be possible to produce and use fuels on a global scale with near zero emissions of air pollutants (nitrogen oxides, carbon monoxide, sulfur oxides, volatile hydrocarbons or particulates) or greenhouse gases. A future energy system based on electricity and hydrogen has long been proposed as an ideal long-term solution to energy related environmental and supply security problems (see Box 1, Hoffmann, 2001).

Balancing hydrogen's attractions are the technical, economic and infrastructure challenges posed by implementing hydrogen as a new fuel. Commercial hydrogen production, storage and transmission technologies exist in the chemical industries, but optimizing them for widespread hydrogen distribution to consumers involves engineering and cost challenges. Hydrogen end-use technologies such as fuel cells are making rapid progress, but are still very expensive compared to existing power sources, although costs are projected to drop in mass production. Developing lightweight, compact, low cost hydrogen storage for vehicles remains an issue. Unlike gasoline or natural gas, hydrogen is not widely distributed today to consumers, and building a hydrogen infrastructure is seen as a daunting challenge.

In this testimony, I review the status of hydrogen technologies, and briefly describe near-term and long-term options for production and delivery of hydrogen for energy uses. The economics and environmental and energy supply aspects of different hydrogen pathways are discussed. Barriers to widespread use of hydrogen are described. Various scenarios are suggested for how a transition might take place from today's energy system to a hydrogen economy. Finally, I discuss the role of public policy in bringing about a hydrogen economy.

STATUS OF TECHNOLOGIES FOR HYDROGEN PRODUCTION AND DELIVERY

Hydrogen Production

Thermochemical Hydrogen Production from Fossil Fuels and Biomass

Hydrogen is widely used today in the chemical and oil refining industries. In the United States about one percent of primary energy use and five percent of natural gas use goes to hydrogen production. Most hydrogen today is made thermo-chemically by processing hydrocarbons (such as natural gas or coal) in high temperature chemical reactors to make a synthetic gas or "syngas," comprised of hydrogen, carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O) and methane (CH_4). The syngas is further processed to increase the hydrogen content and pure hydrogen is separated out of the mixture.

Steam Reforming of Natural Gas: About 95 percent of industrial hydrogen in the United States is produced thermo-chemically from natural gas via "steam methane reforming," where natural gas reacts with steam in the presence of a catalyst to make a syngas. Steam methane reforming is a mature, commercial technology for large-scale hydrogen production for the chemical and oil refining industries. In many areas of the world where low cost natural gas is available, including the United States, steam reforming is generally the lowest cost source of hydrogen over a wide range of plant sizes. A variety of systems are under development and demonstration for small scale production of hydrogen from natural gas, at a scale appropriate for vehicle refueling stations or fuel cells in buildings.

Coal Gasification: Hydrogen can also be produced at large scale by gasification of solid fuels such as coal or petroleum coke. The chemical process technologies to produce hydrogen from coal are commercially available. Advanced systems for production of electricity and hydrogen from coal with CO_2 capture are under development.

CO_2 Capture and Sequestration: When hydrogen is made from fossil fuels, carbon dioxide can be separated, compressed, transported by pipeline and "sequestered" in secure underground storage sites such as deep saline aquifers or depleted oil and gas fields. This would allow continued use of fossil-derived transportation fuels, with near-zero emissions of carbon to the atmosphere. The technologies for capturing, transporting and injecting carbon dioxide into geological formations are well known in the oil industry where carbon dioxide is piped and injected into oil reservoirs for enhanced oil recovery. Several demonstrations of CO_2 sequestration are ongoing in the United States and Europe. However, there are still many unanswered scientific and cost questions about long-term storage of carbon dioxide. Carbon capture and sequestration are important enabling technologies for fossil hydrogen as a long-term, low carbon emitting option.

Gasification of Biomass and Wastes: Gasification of biomass or wastes (such as municipal solid waste) could be used to produce hydrogen, in a process similar to coal gasification. In regions with plentiful, low cost biomass resources, biomass gasification could be an economically attractive method of hydrogen production. The technologies to produce hydrogen via biomass gasification are near-term.

Electrolytic Hydrogen Production

In water electrolysis, electricity is passed through a conducting aqueous electrolyte, breaking down water into its constituent elements hydrogen and oxygen. Any source of electricity can be used, including intermittent (time varying) sources such as off-peak power and solar or wind electricity. Various types of electrolyzers are in use. Commercially available systems today are based on alkaline technology. Proton exchange membrane (PEM) electrolyzers have been demonstrated, are in the process of being commercialized and hold the promise of low cost. Experimental designs for electrolyzers have been developed using solid oxide electrolytes and operating at temperatures of 700 to 900°C. High temperature electrolysis systems offer higher efficiency of converting electricity to hydrogen, as some of the work to split water is done by heat, but materials requirements are more severe. Advances in electrolysis technologies are likely to reduce costs and improve conversion efficiencies. The production cost of electrolytic hydrogen is strongly dependent on the cost of electricity. Electrolytic systems are generally competitive with steam reforming of natural gas only where low cost (1–2 cent/kWh) power is available. Electrolysis is a modular technology that can be used over a wide range of scales from household to large central hydrogen plants serving a large city. Small-scale electrolysis systems for hydrogen production at refueling stations are being demonstrated, as part of hydrogen vehicle programs.

Hydrogen from Off-peak Power: Off-peak power could be a locally important resource for electrolytic hydrogen production, particularly in areas where low cost excess hydropower or geothermal power is available. However, the total amount of hydrogen that could be made from off-peak power is considerably less than projected future needs for fuels. While locally important, off-peak power is unlikely to supply all the hydrogen that would be needed in a hydrogen economy (Williams, 2003). Depending on the source of the off-peak electricity, the full fuel cycle emissions of carbon from hydrogen production could be zero (for hydropower or nuclear power) to quite large (for coal-fired power plants without CO_2 sequestration). ("Full fuel cycle" emissions include all emissions associated with extraction of primary resources such as coal or natural gas, conversion of primary resources to hydrogen, hydrogen transmission to users, and hydrogen use. For vehicles, "full fuel cycle" emissions are also referred to as "well-to-wheels" emissions.)

Hydrogen from Wind or Solar Power: It has been proposed that solar or wind electricity could be used to produce hydrogen electrolytically in a "zero emission" fuel cycle. Solar and wind are potentially huge resources that could produce enough hydrogen to satisfy human needs for fuels, with zero emissions of greenhouse gases and air pollutants. Solar photovoltaic (PV) and wind powered electrolysis are technically feasible: the issue is cost. Electrolytic hydrogen from intermittent renewable sources is generally two to three times more costly to produce than hydrogen made thermo-chemically from natural gas or coal, even when the costs of CO_2 sequestration are added to the fossil hydrogen production cost. Solar or wind hydrogen costs more primarily because of the high cost of electricity input for electrolysis, as compared to the lower cost of feedstocks like natural gas or coal for thermo-chemical processes.

Thermo-chemical water splitting cycles

It is thermodynamically possible to split water directly into hydrogen and oxygen using heat at 4000 C, although is impractical to work at these high temperatures with current materials. However, water splitting can also be accomplished through a complex series of coupled chemical reactions driven by heat at 400–900 C from nuclear reactors or solar concentrators. A number of thermo-chemical water splitting cycles have been investigated for use with nuclear or solar heat (Yalçin, 1989). A recent assessment of nuclear hydrogen production (Brown, 2002) identified the sulfur-iodine process as one of the most promising cycles. Thermo-chemical water splitting cycles are still undergoing research, and are not as technically mature as fossil hydrogen production systems such as steam reforming, coal gasification or water electrolysis, and should be considered a longer-term possibility. A recent analysis by Williams (2003) indicated that nuclear thermo-chemical hydrogen might cost about 80 percent more to produce than hydrogen from coal with CO_2 sequestration, assuming all the cost and performance goals are met for thermo-chemical processes and nuclear plants.

Other Experimental Methods of Hydrogen Production

Fundamental research is being conducted on a variety of experimental methods of hydrogen production including direct conversion of sunlight to hydrogen in electrochemical cells and hydrogen production by biological systems such as algae or bacteria. These methods are far from commercialization.

Economics of hydrogen production systems

In Figure 1, we estimate the capital cost of commercial and near-commercial hydrogen production systems versus size. Capital costs are given in terms of dollars per kilowatt ($/kW) of hydrogen output versus plant size. The plant size is given in kW and in terms of the number of hydrogen fuel cell cars that could be fueled. Small hydrogen production systems suitable for use at refueling stations are shown at the left, and large central hydrogen plants at the right. Steam methane reformers (SMR) and coal gasification plants are shown with and without CO_2 capture. SMRs are available at both small and large size. When small SMRs are produced in quantity, with a standardized design, the capital cost is projected to decrease. (Note that the capital cost per kW is projected to fall by about a factor of 2 for each ten-fold increase in production of small SMR units. Small SMRs are under development, so these "mass-produced" costs have not yet been achieved in commercial systems.) Coal gasification systems are large plants that could serve about one million fuel cell cars. Coal gasification systems have a higher capital cost per unit of hydrogen output than steam reformers or advanced electrolyzers. We have also shown a data point for nuclear thermo-chemical hydrogen, although costs for this less developed option should be regarded as more uncertain than those shown for the other large scale technologies. Hydrogen production systems exhibit scale economy, both in plant size, and, for small systems in the number of units produced.

Hydrogen delivery to consumers: hydrogen storage, transmission, distribution and refueling

Hydrogen Storage

Unlike gasoline or alcohol fuels, which are easily handled liquids at ambient conditions, hydrogen is a light-weight gas, and has the lowest volumetric energy density of any fuel at normal temperature and pressure. Thus, hydrogen must be stored as a compressed gas (in high pressure gas cylinders), as a very low temperature or cryogenic liquid at $-253^{\circ}C$ (in a special insulated vessel or dewar) or in a hydrogen compound where the hydrogen is easily removed by applying heat (such as a metal hydride). All these storage methods for hydrogen are well known in the chemical industry.

Large-scale bulk storage of industrial hydrogen is typically done as a compressed gas or a cryogenic liquid. Very large quantities of hydrogen can be stored as a compressed gas in underground geological formations such as salt caverns or aquifers.

Hydrogen onboard storage systems for vehicles are bulkier, heavier and costlier than those for liquid fuels (like gasoline or alcohols) or compressed natural gas, but are less bulky and heavy than electric batteries. Even with these constraints, it appears that hydrogen could be stored in high pressure (5000 psi or 340 atmospheres) gas cylinders at acceptable cost, weight and volume for vehicle applications (James et al., 1996; Thomas et al., 1998). This is true because hydrogen can be used so efficiently that relatively little energy is needed onboard to travel a long distance.

Innovative storage methods such as hydrogen adsorption in carbon nano-structures and chemical hydrides are being researched (DOE Hydrogen Storage Workshop 2002). Development of a novel hydrogen storage medium that required neither high pressure nor low temperature would not only facilitate use of hydrogen on vehicles, but could reduce hydrogen infrastructure costs and complexity as well.

Hydrogen Transmission and Distribution

The technologies for routine handling of large quantities of hydrogen have been developed in the chemical industries. Hydrogen can be liquefied at low temperature (−253°C) and delivered by cryogenic tank truck or compressed to high pressure and delivered by truck or gas pipelines. While most hydrogen is produced and consumed where it is needed, a small fraction (perhaps five percent) termed "merchant hydrogen" is distributed via truck or pipeline to distant users. The merchant hydrogen system could provide some of the technological building blocks to put a hydrogen refueling infrastructure in place. Developing a hydrogen infrastructure for vehicles poses special challenges in matching hydrogen supply to demand, discussed in the next section (chicken and egg problem).

There are several hundred miles of high-pressure hydrogen pipelines in operation in the United States and in Europe. Long distance hydrogen pipeline transmission costs perhaps 1.5–3 times as much as natural gas transmission per unit of energy delivered.

For local distribution of hydrogen to users such as refueling stations, high pressure, small diameter pipelines analogous to natural gas utility "mains" might be used. The cost of building local distribution pipelines through an urban area is likely to be quite high, on the order of $1 million/mile, depending on the area. A large and geographically dense demand would be required for cost-effective local hydrogen pipelines. This might not occur until 10–25 percent of the cars in a typical urban area converted to hydrogen.

Like electricity, hydrogen can be made from a variety of widely available primary sources. This is quite different than the situation for natural gas or oil, which occur in limited geographical areas. Moreover, it is usually less expensive to bring a primary energy source natural gas or coal to a hydrogen plant located at the "city gate," than it would be to make hydrogen at the gas field or coal mine and pipe it to the city. It is unlikely that transcontinental hydrogen pipelines would be built, unless there was a compelling reason to make hydrogen in a particular location far from demand. Rather hydrogen would be derived from regionally available resources.

Hydrogen Refueling Stations

The design of hydrogen refueling stations depends on how hydrogen is stored onboard the car, as well as demand patterns, and how many cars are served per day. A number of approaches are being tried for refueling hydrogen vehicles. There are currently about 60 hydrogen refueling stations worldwide for experimental vehicles.

NEAR-TERM AND LONG-TERM PATHWAYS FOR HYDROGEN PRODUCTION AND DELIVERY

In Figures 2 and 3, we illustrate various options for supplying hydrogen transportation fuel in the near-term and long-term. (It is assumed that fuel is delivered to cars as a high pressure gas.)

Near-term options include:

- Central steam reforming of natural gas with distribution of hydrogen via compressed gas or liquid hydrogen truck or pipeline.
- Recovery of hydrogen from chemical processes with distribution of hydrogen.
- Onsite production of hydrogen via small scale steam reforming of natural gas at the refueling station.
- Onsite production of hydrogen via small scale water electrolysis at the refueling station.

Long-term central hydrogen supply options include:

- Centralized production of hydrogen via electrolysis with distribution of hydrogen.
- Solar or wind powered electrolysis.
- Gasification of coal, petcoke, biomass or wastes.
- Thermo-chemical water splitting powered by high temperature nuclear or solar heat.

All the near-term options shown can be realized with commercially available technology, although small scale onsite production systems are undergoing rapid development for refueling station applications. Of the long-term options shown, all are based on commercial or near-commercial technology, except thermo-chemical water splitting systems, which should be regarded as less technically mature than gasification-based systems or electrolyzers.

Comparison of Hydrogen Production and Delivery Pathways

Economics

Delivered Cost of Hydrogen

In Figure 4, we compare the delivered cost of hydrogen transportation fuel from various near-term and long-term options. The delivered fuel cost includes the cost of producing hydrogen, distributing it to refueling stations and delivering it to vehicles at high pressure (5000 psi or 340 atmospheres). Costs are given in $/kilogram of hydrogen. (One kilogram of hydrogen contains roughly the same amount of energy as one gallon of gasoline. So a delivered fuel cost of $2/kg hydrogen is roughly equivalent to a fuel cost of $2/gallon gasoline.) Costs for the feedstocks for hydrogen production (natural gas, coal, etc.) are based on Energy Information Administration (EIA) projections for 2020. Although hydrogen costs more than gasoline, it can be used more efficiently in the car, so that the fuel cost per mile is comparable. For our assumptions (appropriate to U.S. conditions), fossil derived hydrogen offers the lowest cost. CO_2 disposal adds relatively little to the cost of hydrogen production from coal. In general, the lowest cost option depends on the local costs of natural gas, coal, and electricity.

Capital Cost of Hydrogen Infrastructure

In Figure 5, we show the capital cost of hydrogen infrastructure for various near- and long-term options. Infrastructure includes hydrogen production, storage, delivery and refueling. For fossil hydrogen production, cases with CO_2 capture and sequestration are included. Depending on the technology, the infrastructure capital cost is several hundred to several thousand dollars per car. Infrastructures based on CO_2-free technologies cost more than earlier infrastructure that relies on steam reforming of natural gas. Of the long-term, low CO_2 options, fossil hydrogen with CO_2 sequestration appears to offer lower capital costs. This graph implies that putting a new hydrogen infrastructure in place for 100 million cars (about half the vehicles in the U.S.) might cost $50–$200 billion.

Emissions of Air Pollutants and Greenhouse Gases

The primary reasons for considering hydrogen as a future fuel are its potential benefits for the environment and energy supply security. Many alternative fuels and efficient, low emission end-use technologies could help address environmental and energy supply challenges. How does H_2 compare to other options with respect to emissions of greenhouse gases and air pollutants and oil use? Several recent studies have estimated the "well to wheels" or full fuel cycle emissions of greenhouse gases and air pollutants for alternative fueled vehicles (Wang, 1999; Weiss et al., 2000; GM et al., 2001).

In Figures 6 and 7, full fuel cycle emissions of air pollutants and greenhouse gases are shown for various alternative fueled vehicles. We compare current gasoline internal combustion engine vehicles (ICEVs) and a variety of lightweight, advanced vehicles: *(i)* ICEVs fueled with gasoline or hydrogen (H_2); *(ii)* internal combustion engine/hybrid electric vehicles (ICE/HEVs) fueled with gasoline, compressed natural gas (CNG), Diesel, Fischer-Tropsch (F–T) liquids or H_2; and *(iii)* fuel cell vehicles (FCVs) fueled with gasoline, methanol or H_2. We consider H_2 derived from natural gas and coal, with and without CO_2 sequestration, and H_2 derived from windpower via electrolysis.

Emissions are normalized to an advanced, lightweight gasoline internal combustion engine vehicle with a fuel economy of 46 mpg, that satisfies stringent Tier II air pollution standards. Today's conventional gasoline cars are also shown for reference. We see that advanced internal combustion engine vehicles and ICE hybrid electric vehicles fueled with gasoline, CNG or Diesel fuel can result in reductions of both air pollutants and greenhouse gases, compared to today's gasoline ICEV technologies. With hydrogen produced from natural gas, well to wheels greenhouse gas emissions are somewhat reduced compared to gasoline or Diesel hybrids, and emissions of air pollutants are significantly lower. Hydrogen produced from renewable sources or fossil fuels with CO_2 sequestration and used in fuel cells stands out as the options with by far the lowest emissions.

Energy Supply Security

It would be possible to make hydrogen from a variety of domestically available sources such as natural gas, coal or renewables. Widespread use of hydrogen would reduce costs associated with oil supply insecurity.

Quantifying the Benefits of Hydrogen: Environmental and Energy Supply Security Externality Costs

Hydrogen can reduce emissions of air pollutants and greenhouse gases compared to other transportation fuels, and decrease use of oil. What is the potential economic benefit?

It is difficult to estimate the external costs of energy precisely, because of the many uncertain variables that go into such a calculation.

- The damage costs of global climate change are highly uncertain. Costs of $50–$200/tonne Carbon are often used as a possible range for the cost of removing carbon from the energy system.
- Air pollution damage costs have been estimated by various authors (Rabl and Spadaro, 2000; Delucchi, 2000). These are primarily associated with long-term health effects of particulates (small particles that are emitted directly from combustion or form in the atmosphere from combustion products). There is a large uncertainty in air pollution damage costs due to uncertainties in knowledge about 1) emissions from sources, 2) atmospheric transport and chemistry, 3) health impacts at a particular level of exposure, and 4) the economic value of damages (disease, premature death). As a result estimates for air pollution damages per kilogram of pollutant emitted range over 1–2 orders of magnitude.
- There is also considerable uncertainty in how to value the costs of oil supply insecurity. We have used a value of $0.35–$1.05/gallon gasoline based on a projected cost of $20–$60 billion per year of expenditures to safeguard oil supply (Ogden, Williams and Larson, 2003).

In Figure 8, we have plotted the lifetime externality costs for different vehicle/fuel combinations over the lifetime of the car, based on an analysis in (Ogden, Williams and Larson, 2003). To derive the damage costs ($ per mile), we combined estimates of full fuel cycle emissions (kilograms per mile) of air pollutants and greenhouse gases (Wang, 1999) with estimates for the damage costs per kilogram of emission ($ per kilogram). To reflect the large uncertainties in, low, median and high externality cost estimates are shown for each vehicle/fuel option. In each bar, three stacked externality costs are shown, representing costs for global climate change, air pollution and oil supply insecurity. We see that there is a tremendous range of uncertainty in these costs. However, hydrogen fuel cell vehicles have by far the lowest externality costs of any option. And they are the least sensitive to the actual value of these highly uncertain costs. At the mid to high end of the externality cost range, hydrogen fuel cell vehicles have a lifetime externality cost that is several thousand dollars less than advanced internal combustion engine hybrid vehicles fueled with gasoline or Diesel. This means that the hydrogen fuel cell vehicle could cost more in the showroom, and still break even in lifecycle costs, if externalities are taken into account.

A lifecycle cost comparison of alternative fueled automobiles is shown in Figure 9 (Ogden, Williams and Larson, 2003). The lifecycle cost includes vehicle first costs (assuming fuel cell vehicle costs projected for large scale mass production), fuel costs, and median externality costs. This shows that hydrogen fuel cell vehicles are approximately competitive with other advanced internal combustion engine cars, when externalities are valued at the median level in Figure 8. In Figure 10, we replot the lifecycle cost with low, median and high externalities. If the high end of the externality cost range is used (right side of Figure 10), the hydrogen fuel cell vehicle is the least cost option. If, on the other hand, externalities are not valued highly (left side of Figure 10), there is little economic reason to switch to hydrogen.

This analysis highlights the importance of externalities as a driver for adopting hydrogen as a transportation fuel. It also suggests that public policies reflecting the value of externalities will probably be needed to bring hydrogen fuel cell vehicles into widespread use.

BARRIERS TO ADOPTION OF HYDROGEN AS AN ENERGY CARRIER

Probably the most significant barriers to widespread use of hydrogen are the current high cost of hydrogen end-use technologies, and the current lack of a hydrogen infrastructure. There is reason for optimism that the cost of hydrogen technologies such as fuel cells can be reduced by large-scale mass production (Thomas et al., 1998). Various strategies for starting a hydrogen infrastructure have been proposed. These include starting with buses or other centrally refueled fleet vehicles, with marine applications, or with hydrogen co-produced in by natural gas reformers in cogeneration systems in buildings. While it is fairly straightforward to envision a fueling system for centrally refueled fleets, moving beyond fleets into general automotive markets is more problematic, especially if the market penetration rate is slow. There is a problem of matching supply to demand, as the market grows (chicken and egg problem).

In addition, although there are adequate methods for large-scale industrial hydrogen production, distribution and storage, technologies better adapted for a hydrogen energy economy could speed progress. For example, development of low cost, onsite hydrogen production systems for refueling stations would facilitate providing a fuel supply for vehicles. The development of a better onboard hydrogen storage system could increase the range of vehicles, and reduce infrastructure costs. Development of carbon sequestration is key for the long-term viability of the fossil hydrogen option.

As mentioned above there is a need for policies reflecting the external costs of energy and encouraging the use of lower emitting, more energy efficient vehicles. There is uncertainty about future markets for hydrogen technologies, because it is uncertain how much its benefits will be valued. To quote from Ogden, Williams and Larson, 2003: "One should expect that externality valuations will change over time both as a result of improved scientific understanding and as a result of shifting societal values. Although externality valuations might decline over time, the long-term trend in the making of energy policy has been toward ever tighter controls on emissions that are thought to entail environmental damages. This trend may well continue both as a result of improved scientific evidence of damages [e.g., Pope et al. (1995) in the case of health damage caused by small-particle air pollutants, and O'Neill and Oppenheimer (2002) in the case of climate change damages], and the increasing importance of environmental issues in the public mind as incomes rise (Williams, 2000). Moreover, as already noted, energy supply insecurity concerns, which were paramount in energy policymaking in the 1970s, have once more become a prominent concern."

POSSIBLE ROUTES TO A HYDROGEN ECONOMY

In industrialized countries, hydrogen might get started by "piggybacking" on the existing energy infrastructure. Initially, hydrogen could be made where it was needed from more widely available energy carriers, avoiding the need to build an extensive hydrogen pipeline distribution system. For example, in the United States, where low cost natural gas is widely distributed, hydrogen could be made initially from natural gas, in small reformers located near the hydrogen demand (e.g., at refueling stations). (Alternatively, hydrogen could be truck- or pipeline-delivered from a large plant serving both chemical and fuel needs, as with merchant hydrogen today.) As a larger, more concentrated demand builds, central "city-scale" H_2 production with local pipeline distribution would become more economically attractive. Eventually, hydrogen might be produced centrally and distributed in local gas pipelines to users, as natural gas is today. A variety of sources of hydrogen might be brought in at this time, including decarbonized fossil fuels with CO_2 sequestration or renewables. Urban areas with a high geographic density of energy demand would be early candidates for pipeline hydrogen systems. In developing countries, where relatively little energy infrastructure currently exists, centralized hydrogen production for vehicles might be phased in earlier. Regions with special concerns, such as islands that depend entirely on costly imported oil, might choose a hydrogen economy based on locally available resources. This path is being pursued in Iceland, which has announced its intention to switch to hydrogen fuel (produced via electrolysis using off-peak power) by 2030.

ENERGY POLICY AND THE HYDROGEN ECONOMY

Are Policies Necessary to Bring About a Hydrogen Economy?

Our research suggests that external costs of energy could become a powerful economic driver for adopting hydrogen technologies (Ogden, Williams and Larson, 2003). Without these, there is little or no economic advantage in hydrogen over conventional technologies. This led us to conclude that a range of policies aimed at internalizing the environmental and security costs of energy will probably be needed to bring about a hydrogen economy. A world where hydrogen is widely used will be a world where externalities are more important than they are now. Political will and markets will evolve together, reflecting profound changes in how we view energy as a society. If we switch to hydrogen, a rapid transition may be more likely than a slow transition. (A rapid hydrogen infrastructure build up might allow a lower cost transition that a slow gradual buildup.)

Another factor that could accelerate the adoption of hydrogen is the potential market pull of fundamentally new products and services enabled by the use of hydrogen or fuel cells. Innovative designs coupled with clean energy could draw customers. Technology breakthroughs could also change the way hydrogen is produced, distributed and used. We did not consider these factors in our analysis. However, we still see a strong role for government leadership in helping nurture hydrogen technologies and coordinate the profound changes in the energy system that hydrogen could bring.

Policy tools to encourage use of hydrogen

Various policies could encourage development of hydrogen energy.

- Research and development on key concepts, where a breakthrough could speed the adoption of hydrogen (e.g., hydrogen storage, small scale hydrogen production, CO_2 sequestration).
- Demonstration of hydrogen production and end-use technologies.
- Policies to encourage "buy-down" of hydrogen technologies such as fuel cells. For example, use of hydrogen in government fleets. Our analysis indicates that centrally refueled fleets are potentially large enough to accomplish significant cost reductions in hydrogen vehicle technologies, while gaining experience with hydrogen supply and refueling systems. This suggests coupling a Zero Emission Vehicle mandate with clean fleet requirements.
- Policies to account for externalities: air pollution standards, feebates for clean efficient vehicles, fuel economy standards, gasoline tax, carbon tax.

When should these policies be put in place? The first two items are happening now. Using fleet regulations to speed adoption of alternative fuel technologies has been tried before, without resounding success. Still, it is one of the only approaches that avoids the chicken and egg infrastructure problem, at least for a while, and deserves reexamination for hydrogen. The hardest and most important set of policies may be the last. Putting policies in place that reflect externalities will require a strong societal consensus, and a shift in how we view energy.

Analysis by our group at Princeton University and other researchers suggests that, even under optimistic assumptions about progress in hydrogen and fuel-cell technologies, it would be several decades before hydrogen fuel-cell vehicle technologies could make a globally significant impact on reducing emissions. It might be necessary to postpone putting policies in place to deal with environmental and security issues, if hydrogen were the only technology that could address them. However, external costs of energy could be reduced significantly compared to today's cars with advanced internal combustion engine technologies available now or within a few years. We feel that it is very important in the near-term to encourage use of more efficient, less polluting internal combustion engine technologies using conventional fuels. These include more efficient gasoline and Diesel internal combustion engine hybrids.

Still, hydrogen holds the greatest long-term promise for dealing simultaneously with air pollution, greenhouse gas emissions, and energy supply diversity. When hydrogen vehicles are ready, emissions could be reduced significantly compared to those from advanced internal combustion engine vehicles. This underscores the importance of research, development and demonstration of hydrogen technologies now, so they will be ready when we need them.

It is highly uncertain today what economic values should be assigned to external costs of energy (climate change, health effects from air pollution, oil supply insecurity). However, the trend of the past few decades has been toward ever-increasing regulation of emissions, and integrated assessment models of global climate change suggest that deep reductions in carbon emissions from energy use will be required to stabilize atmospheric carbon dioxide at acceptable levels. Depending on how we as a society ultimately value the external costs of energy, hydrogen might well become the long-term fuel of choice.

Should long-term concepts like hydrogen and fuel-cell vehicles have high priority, given that relatively modest improvements in more traditional internal combustion engine technologies could help address environmental and energy supply problems much sooner? In my view, hydrogen and fuel-cell technologies, although high-risk and long-term, have a potentially very high payoff. Therefore, they deserve significant government support now, as "insurance," so that they will be ready in 15–20 years, if and when we need to deploy them widely.

I would encourage a comprehensive strategy, based on developing and encouraging the use of clean, efficient internal combustion engine vehicles in the near-term, coupled with a long-term strategy of research, development and demonstration of hydrogen and fuel cells. Consistent policies to encourage use of cleaner transportation systems with lower carbon emissions and to move away from our almost exclusive dependence on crude oil-derived transportation fuels would encourage adoption of advanced internal combustion engine vehicles in the near-term and, eventually, of hydrogen vehicles.

Box 1. Historical Perspective on the Hydrogen Economy

Although it is not considered a commercial fuel today, hydrogen has been used for energy since the 1800s. Hydrogen is a major component (up to 50% by volume) of synthetic gases ("syngas") manufactured from gasification of coal, wood or wastes. Syngas was widely used in urban homes for heating and cooking in the United States from the mid-1800s until the 1940s, and is still used in many locations around the world (including parts of Europe, South America and China), where natural gas is unavailable or costly. Hydrogen-rich synthetic gases have also been used for electric generation. Hydrogen is an important feedstock for oil refining, and indirectly contributes to the energy content of petroleum-derived fuels such as gasoline. Liquid hydrogen is used as a rocket fuel, and has been proposed as a fuel for supersonic aircraft. Primary energy use for hydrogen production for energy applications (including oil refining) is about one percent of global primary energy use today.

The concept of a "hydrogen economy" (or large scale hydrogen energy system) has been explored several times, first in the 1950s and 1960s as a complement to a largely nuclear electric energy system (where hydrogen was produced electrolytically from off-peak nuclear power), and later as a storage mechanism for intermittent renewable electricity such as solar photovoltaics and wind power. More recently, the idea of a hydrogen energy system based on production of hydrogen from fossil fuels with separation and sequestration (e.g. secure storage underground in depleted gas wells or deep saline aquifers) of byproduct CO_2 has been proposed. There is also renewed interest in advanced water splitting cycles run on nuclear or solar heat, and a on variety of longer term solar electrochemical and biological hydrogen production methods.

Over the past decade there has been an upsurge of interest in hydrogen driven by several factors (Hoffmann 2001). One is the interest worldwide in "zero emission vehicles" to combat urban air pollution. Concerns about global climate change have motivated new interest in low carbon or non-carbon fuels. Hydrogen can be produced from a wide variety of feedstocks, which is attractive for enhancing energy supply security, especially in the transportation sector. Recent rapid progress and industrial interest in low temperature fuel cells such as proton exchange membrane fuel cells (which prefer hydrogen as a fuel) for transportation and power applications has also led to a reexamination of hydrogen as a fuel. As of 2003, most major automotive manufacturers are developing hydrogen powered vehicles, and several major oil companies are involved in demonstrations of hydrogen refueling systems. In 2002 President Bush announced the FreedomCar program to develop a hydrogen fuel cell vehicle.

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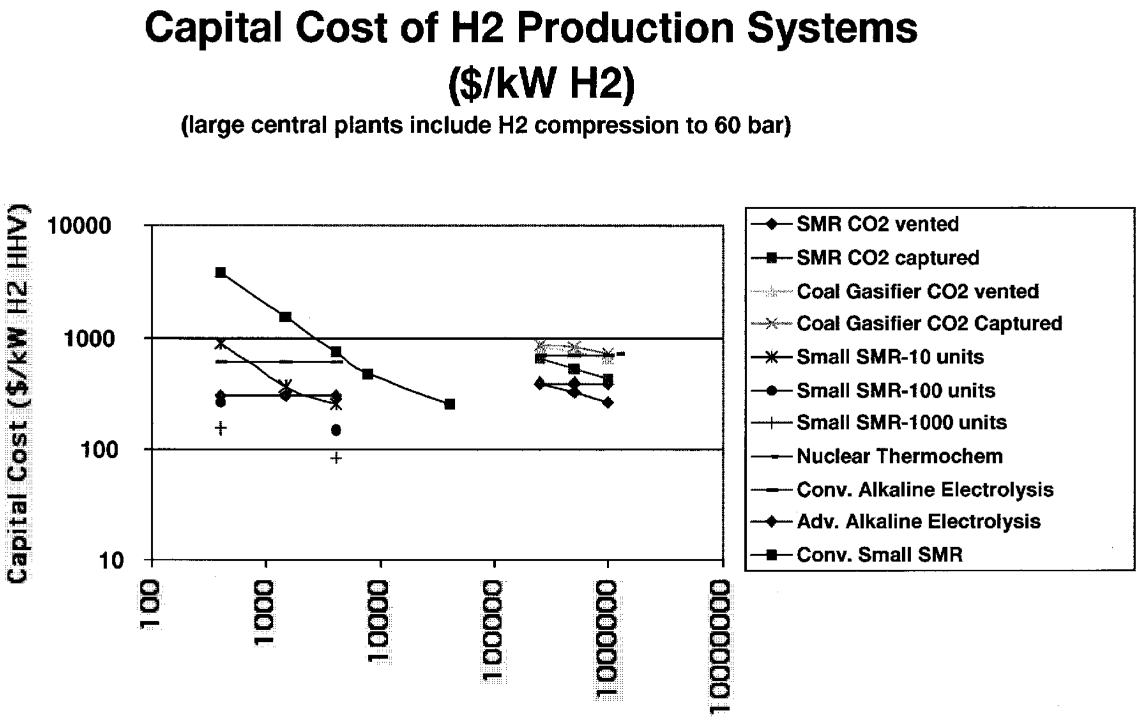


Capital Cost of H2 Production Systems
($/kW H2)
(large central plants include H2 compression to 60 bar)

Figure 1

Figure 2

Near term H_2 Supply Options

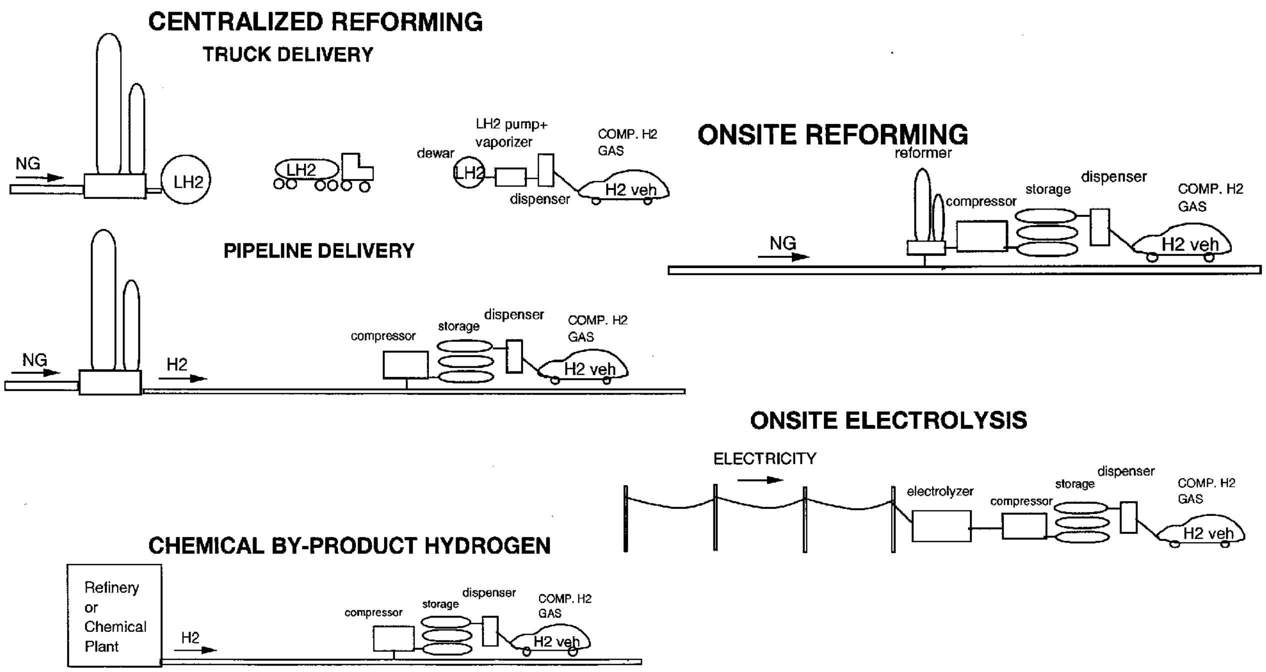
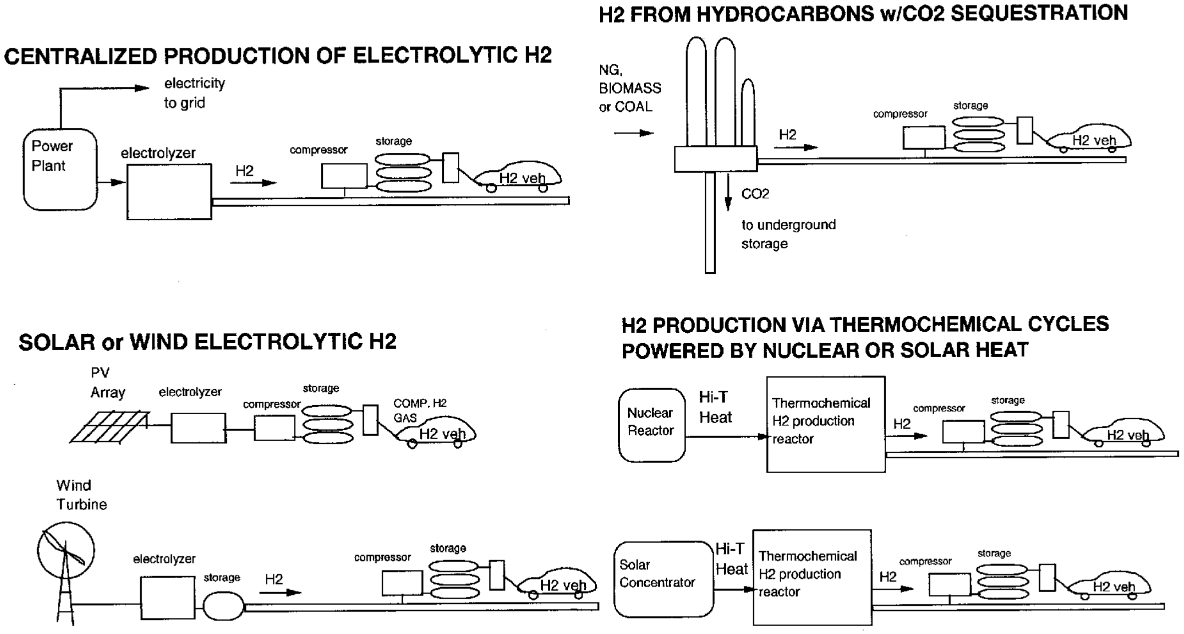


Figure 3.

Long term H_2 Supply Options



CENTRALIZED PRODUCTION OF ELECTROLYTIC H2

H2 FROM HYDROCARBONS w/CO2 SEQUESTRATION

SOLAR or WIND ELECTROLYTIC H2

H2 PRODUCTION VIA THERMOCHEMICAL CYCLES POWERED BY NUCLEAR OR SOLAR HEAT

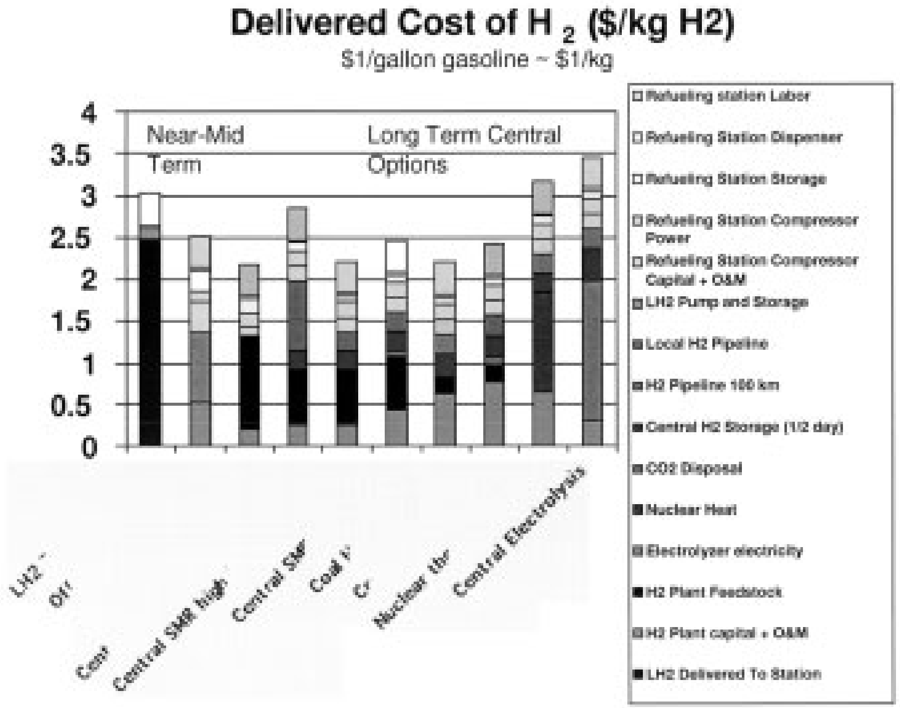

Delivered Cost of H 2 ($/kg H2)
$1/gallon gasoline ~ $1/kg
4
3.5
3
2.5
2
1.5
1
0.5
0
Near-Mid Term
Long Term Central Options
LH2 -
Of
Cen
Central SMR high
Central SM
Coal
C
Nuclear thr
Central Electrolysis
Refueling station Labor
Refueling Station Dispenser
Refueling Station Storage
Refueling Station Compressor Power
Refueling Station Compressor Capital + O&M
LH2 Pump and Storage
Local H2 Pipeline
H2 Pipeline 100 km
Central H2 Storage (1/2 day)
CO2 Disposal
Nuclear Heat
Electrolyzer electricity
H2 Plant Feedstock
H2 Plant capital + O&M
LH2 Delivered To Station

Figure 4

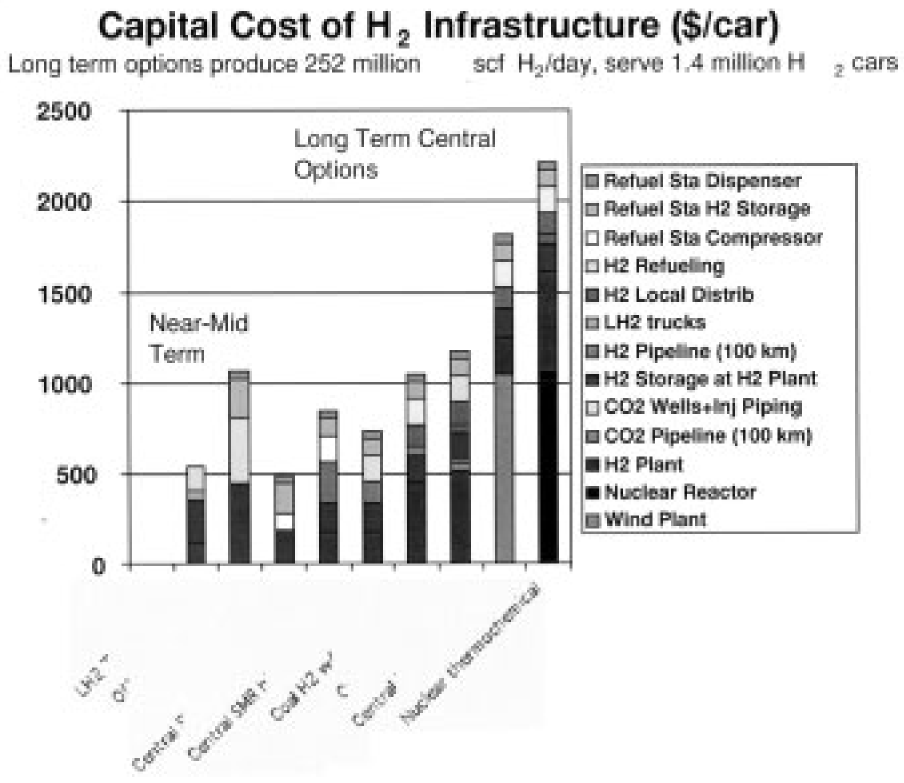

Capital Cost of H_2 Infrastructure ($/car)
Long term options produce 252 million scf H_2/day, serve 1.4 million H_2 cars
2500
2000
1500
1000
500
0
Long Term Central Options
Near-Mid Term
▨ Refuel Sta Dispenser
▨ Refuel Sta H2 Storage
☐ Refuel Sta Compressor
☐ H2 Refueling
■ H2 Local Distrib
▨ LH2 trucks
▨ H2 Pipeline (100 km)
■ H2 Storage at H2 Plant
☐ CO2 Wells+Inj Piping
▨ CO2 Pipeline (100 km)
■ H2 Plant
■ Nuclear Reactor
▨ Wind Plant
LH2
O
Central
Central SMR
Coal H2 w/
C
Central
Nuclear thermochemical

Figure 5.

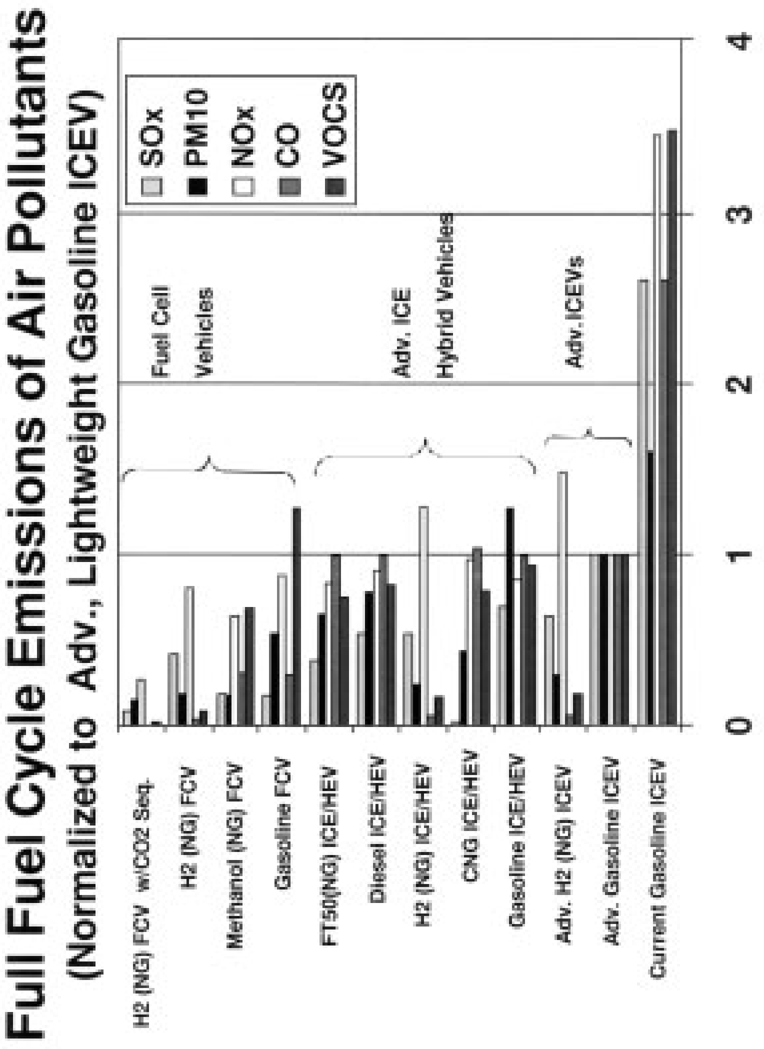

Full Fuel Cycle Emissions of Air Pollutants
(Normalized to Adv., Lightweight Gasoline ICEV)
H2 (NG) FCV w/CO2 Seq.
H2 (NG) FCV
Methanol (NG) FCV
Gasoline FCV
FT50(NG) ICE/HEV
Diesel ICE/HEV
H2 (NG) ICE/HEV
CNG ICE/HEV
Gasoline ICE/HEV
Adv. H2 (NG) ICEV
Adv. Gasoline ICEV
Current Gasoline ICEV
Fuel Cell
Vehicles
Adv. ICE
Hybrid Vehicles
Adv. ICEVs
SOx
PM10
NOx
CO
VOCS
0
1
2
3
4

Figure 6

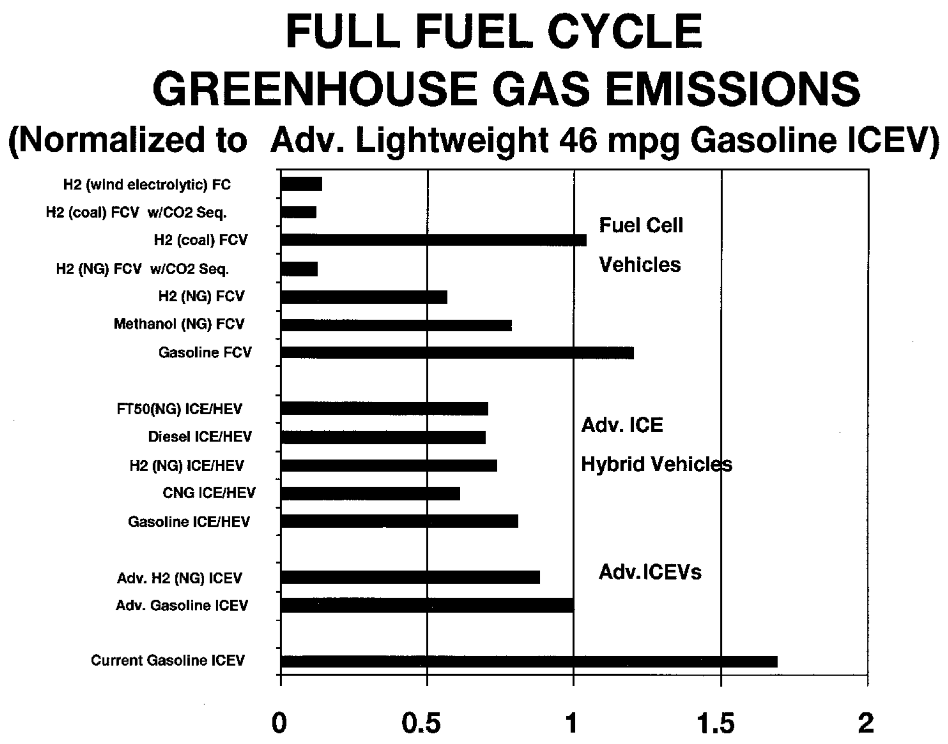
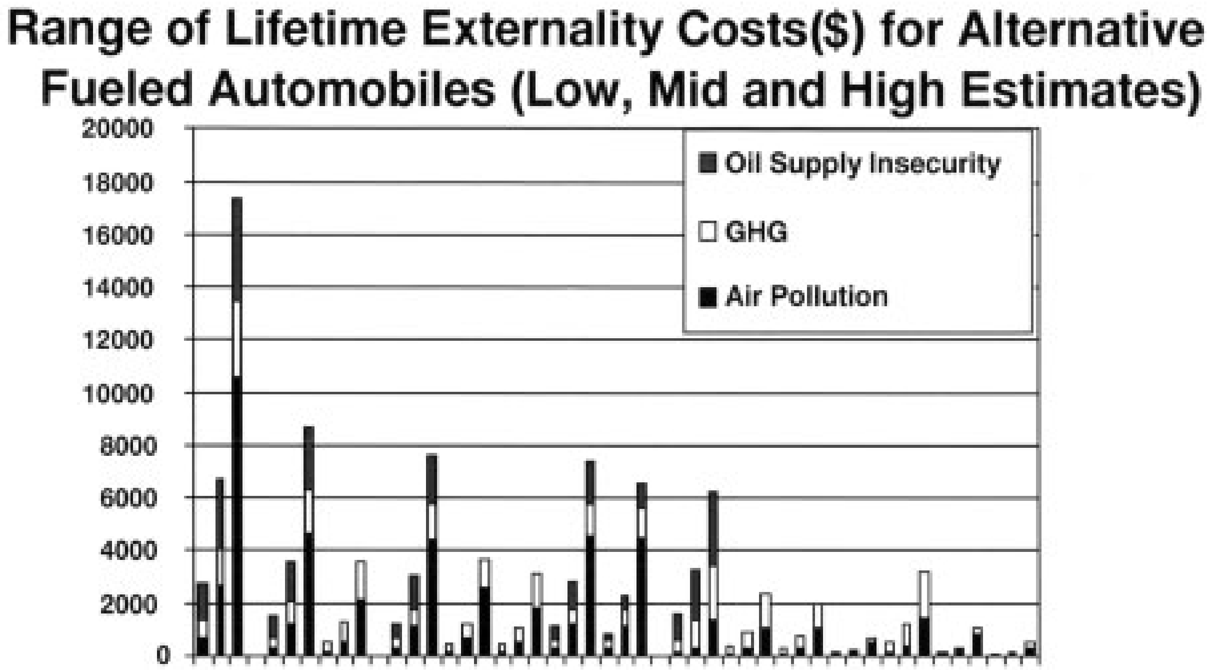
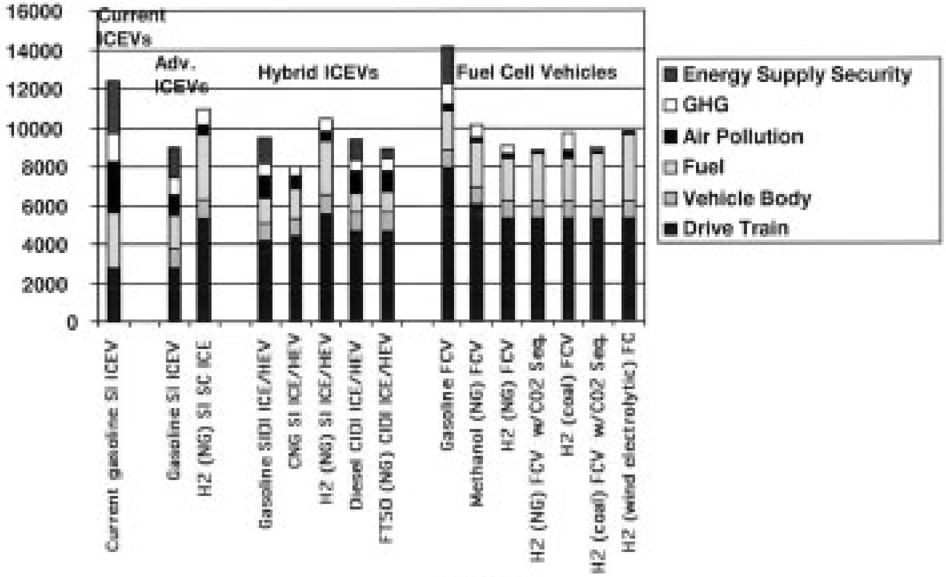

FULL FUEL CYCLE
GREENHOUSE GAS EMISSIONS
(Normalized to Adv. Lightweight 46 mpg Gasoline ICEV)
H2 (wind electrolytic) FC
H2 (coal) FCV w/CO2 Seq.
H2 (coal) FCV
H2 (NG) FCV w/CO2 Seq.
H2 (NG) FCV
Methanol (NG) FCV
Gasoline FCV
FT50(NG) ICE/HEV
Diesel ICE/HEV
H2 (NG) ICE/HEV
CNG ICE/HEV
Gasoline ICE/HEV
Adv. H2 (NG) ICEV
Adv. Gasoline ICEV
Current Gasoline ICEV
Fuel Cell
Vehicles
Adv. ICE
Hybrid Vehicles
Adv.ICEVs
0
0.5
1
1.5
2

Figure 7

Figure 8


Range of Lifetime Externality Costs($) for Alternative Fueled Automobiles (Low, Mid and High Estimates)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Oil Supply Insecurity
GHG
Air Pollution

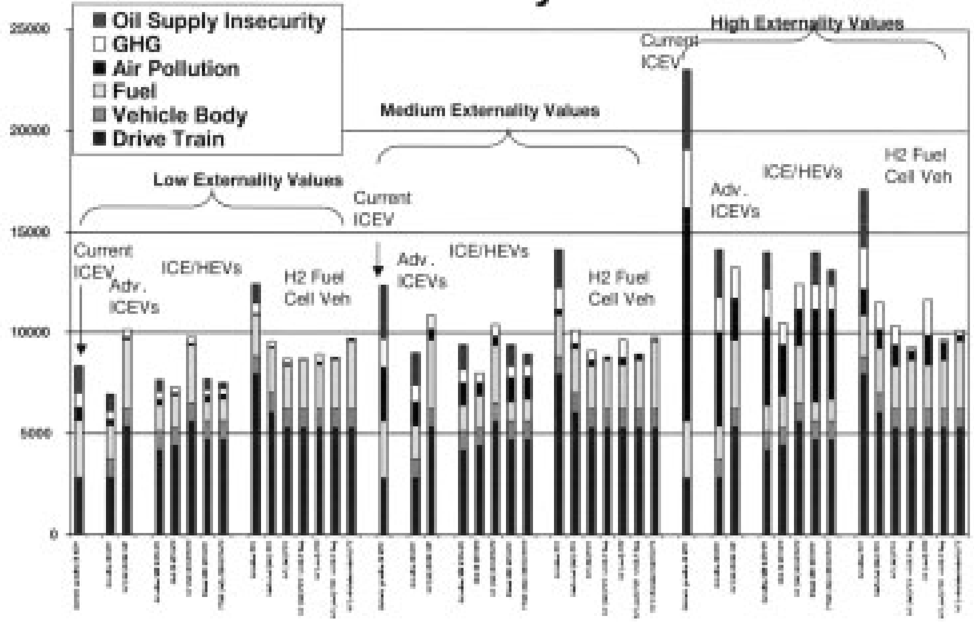


Societal Lifecycle Cost ($) for Alt. Fueled Cars Including Drive Train, Lightweight Body, Fuel, and Externality Costs for Air Pollution, Greenhouse Gases, & Oil Supply Insecurity

Figure 9

Figure

Lifecycle Cost($) of Alternative Fueled Automobiles for Low, Median and High Externality Values



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SYNOPSIS: My graduate education centered on physics, mathematics and numerical simulation techniques, culminating in a Ph.D. in theoretical plasma physics in 1977. For several years I did research in nuclear fusion energy, first as a research associate at the Princeton Plasma Physics Laboratory and later as an independent consultant to the U.S. Department of Energy. During this time I also worked in other areas of applied physics, particularly the field of image processing where I hold several patents. A developing interest in broader energy questions led me to Princeton University's Center for Energy and Environmental Studies, Princeton Environmental Institute, where I have worked since 1985. Most of my research has involved technical and economic assessments of new energy technologies, characterized by low emissions of pollutants and greenhouse gases and high conversion efficiency. Particular areas of interest are production of low polluting fuels, the use of hydrogen as an energy carrier and applications of fuel cell technology in transportation and stationary power production. Over the past several years I have carried out a series of assessments of fuel cell vehicles and hydrogen refueling infrastructure for the USDOE Hydrogen R&D Program and Fuel Cell Program. I have served on a number of high level panels for the US Department of Energy on Hydrogen, Carbon Sequestration and Fuel Cell Research, most recently as a contributor to the November 2001 Hydrogen Vision Meeting and leader of the "Integration Team" at the April 2002 Hydrogen Roadmap meeting. I have published over 100 technical articles on energy topics including one book, six book chapters and numerous peer reviewed articles and conference presentations.

EDUCATION:

B.S. with high honors, mathematics, University of Illinois, Champaign-Urbana, 1970.

Ph.D. in physics, University of Maryland, College Park, MD, 1977 (thesis: plasma physics theory, computer simulation).

Post-Doctoral Research Associate, Princeton Plasma Physics Laboratory, Princeton University 1977–1979.

POSITIONS HELD:

Center for Energy and Environmental Studies, Princeton Environmental Institute, Princeton University

Research Scientist (1993–present)

Research Staff (1987–1993)

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Consultant (1982–1984)

Member of the Technical Staff (1984–1985)

Self-Employed Consultant in Applied Physics 1980–1985

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Princeton University

Princeton Environmental Institute
Princeton University
27 Guyot Hall
Princeton, MJ 08544

March 3, 2003

The Honorable Sherwood L. Boehlert
Chairman, House Science Committee
2320 Rayburn House Office Building
Washington, D.C. 20515

Dear Chairman Boehlert,

Thank you for the opportunity to testify before the House Science Committee as part of your March 5th hearing on *The Path to a Hydrogen Economy.* As per the Rules of the Committee on Science, I am writing to disclose the sources of federal support I currently receive for my research on hydrogen energy and carbon sequestration.

1. Sponsor: National Renewable Energy Laboratory (NREL)
   Title: Technical and Economic Assessment of Transition Strategies Toward Widespread Use of Hydrogen as an Energy Carrier
   Award Number: XCM-2-32067-01(Prime DE-AC36-99GO10337)
   Award Amount: $335,365.84

2. Sponsor: DOE - Washington
   Title: IIPS: Conceptual Design of Optimized Fossil Energy Systems With Capture and Sequestration of Carbon Dioxide
   Award Number: DE-FC26-02NT41623
   Award Amount: $202,365

Again, thank you for the opportunity to participate in this hearing.

Sincerely,

Joan M. Ogden, Ph.D.

Chairman BOEHLERT. Thank you very much. Dr. Burns.

STATEMENT OF DR. LAWRENCE D. BURNS, VICE PRESIDENT, RESEARCH DEVELOPMENT AND PLANNING FOR GENERAL MOTORS

Dr. BURNS. I appreciate the opportunity to be here today to testify on behalf of General Motors. And I am Larry Burns, Vice President of R&D and Planning for GM. I have responsibility for driving innovation and to GM's vehicles today, and directing GM's reinvention of the automobile around promising new technologies like fuel cells and bi-wire systems. GM's goal is to realize sustainable mobility vehicles that are more exciting, more compelling, and more affordable than the vehicles that people have available today. And these are vehicles that people really want to drive and buy.

We believe fuel cells and hydrogen hold the key to realizing this goal. We expect to begin selling hydrogen fuel cell vehicles by 2010. And GM hopes to be the first manufacture to sell one million fuel cell vehicles profitably. In support of these goals, today, GM and Shell are announcing a new demonstration program in Washington DC area designed to be a real world trial of hydrogen fuel cells and hydrogen fueling technology.

Before we see fuel cell vehicles on the roadways in large volumes, however, a number of technical challenges must be addressed. We see cost, durability, fuel infrastructure, and storage as the major barriers to commercialization of fuel cell vehicles. In addition, more emphasis must be placed on hydrogen production emphasis or technology research.

With respect to the vehicle, hydrogen storage is the toughest hurdle. Liquid and compressed gas and solid state storage methods are all promising, but present technical challenges and cost challenges. GM has demonstrated both liquid and compressed hydrogen storage tanks in our prototype vehicles. And we are also doing research on various forms of solid state storage, but given the magnitude of the storage challenge, a significantly expanded federal R&D effort in this area is both necessary and appropriate.

If we are successful in bringing fuel cell vehicles to market at the beginning of the next decade, the result will be a growing demand for conveniently available hydrogen. Looking out over a 20 year time frame, we believe we should begin today to look for better and more sustainable means of producing hydrogen as a vehicle fuel. Like hydrogen storage, we believe this is a challenge and also warrants a significantly expanded R&D effort.

Cost is another major challenge, and we are making very important progress in this area. GM has achieved a cost improvement with each new generation of our fuel cell stack technology. In addition, we believe that revolutionary vehicle designs, like our autonomy concept and high wire prototype, which combine fuel cells and by-wire electronics and other advanced technologies, could make fuel cell vehicles more affordable and even more compelling. These designs enable dramatically fewer vehicle components, a long life chassis, and significantly fewer vehicle architecture, a result of which have a potential to reduce manufacturing costs.

If we were producing our current fuel cell technology at a scale of over 1,000 stacks per year, we estimate that we could—would be able to produce these at a cost ten times higher than what is required to support wide-spread affordable application in automobiles. But also, this is within what is required for competitive distributed generation products. To put this magnitude of improvement in perspective, the computer industry has brought down the cost of computer memory over a 15 year period by a factor of 3,000, from $17,000 per gigabyte to $6.00 per gigabyte. And the challenge we face with fuel cells requires the same type of molecular material breakthroughs.

Similarly, we do not think the cost of producing hydrogen will be a show-stopper. Petroleum companies have said hydrogen can be generated from natural gas at the refinery at a cost that is comparable on a per mile cost basis to conventional fuels, taken into account the efficiency of fuel cells. Most of the cost of hydrogen comes from its expense of transporting and dispensing it.

The fueling infrastructure is another challenge. However, one of the most exciting aspects of hydrogen is that there are many pathways for producing and delivering it. Hydrogen could be generated at a local filling station, as we know them today, using an appliance like device called the reformer. It also has the potential for refueling of home or places of business using an appliance called an electrolaphiser or natural gas reformer. This takes advantage of the fact that water and electricity and a natural gas are already available in our homes and in many of our businesses.

GM sees distributed generation as a key stepping stone to hydrogen fuel cells vehicles in the early development of the hydrogen infrastructure. We also recently announced that we will conduct a demonstration of a 75 kilowatt direct hydrogen unit in both the U.S. and Japan. This system is intended for uninterruptible power supply systems, such as hospitals, high-reliability data communications, and to handle peak power demands. We expect to market this unit in the 2005 timeframe. And as to reduce the cost to get to automobile scale applications, you open up many attractive business applications for fuel cells and stationary.

GM has always believed that it will take a three-way partnership involving the auto industry, energy companies, and government to successfully commercialize hydrogen fuel cells for vehicles and stationary applications. We applaud President Bush's new hydrogen initiative and his vision for the hydrogen future, and the fact that he has elevated it as a national priority. We would welcome a measure welcome a major new national R&D initiative on hydrogen storage and production. We also believe the Department of Transportation should undeclared hydrogen as a hazardous material and treat it as a fuel. Next, the government should take the lead on development of a national template for the codes and standards that will be required for hydrogen and fuel cells. And finally, every federal agency will have a role in the transition to the hydrogen economy, and they should begin that process today by elevating the use and impact of hydrogen and fuel cell technologies on their operations.

To this end, I would just caution that demonstration projects are costly to do, and they require significant resources. The same resources we are using to refine the fuel cell technology, particularly on the vehicle side. In the next couple of years, the goal should be to have limited number of small scale but integrated demonstration projects, and then later in the decade to expand those projects.

Within GM, the magnitude of our fuel cell investment creates an intense business dilemma—the choice between using our resources to achieve a revolutionary vision or funding the aggressive pursuit of more incrementally focused initiatives. The decisions that we must make in resolving this internal debate will certainly be influenced by the development of a long-term stable set of government policies and initiatives upon which we can properly balance the investment of our finite financial and technical resources. Thank you very much.

[The prepared statement of Dr. Burns follows:]

Prepared Statement of Lawrence D. Burns

I appreciate the opportunity to be here today to testify on behalf of General Motors. I am Larry Burns, Vice President of Research & Development and Planning for GM. I have responsibility for driving innovation into today's vehicles and directing GM's reinvention of the automobile around promising new technologies like fuel cells and by-wire systems. GM's goal is to realize sustainable mobility with exciting, compelling, and affordable vehicles that people will want to drive and buy.

We are on record saying that we expect to begin selling hydrogen fuel cell vehicles by 2010, and GM hopes to be the first manufacturer to sell one million fuel cell vehicles. In support of these goals, in the next few years, we will be fielding small demonstration fleets to test the viability of fuel cell technology. In fact, later today, GM and Shell will announce a new demonstration program in the Washington, D.C. area designed to be a real-world trial of hydrogen fuel cell vehicles and hydrogen fueling technology. Larger fleet demonstrations will follow as we ramp up to commercialization.

Before we see fuel cell vehicles on the roadways in large volumes, however, a number of technical challenges must be addressed. The Department of Energy's recently released Fuel Cell Report to Congress identifies cost, durability, fuel infrastructure, and hydrogen storage as the major barriers to commercialization. In addition, the Report states that more emphasis must be placed on research into hydrogen production technologies.

With respect to the vehicle, hydrogen storage is the toughest hurdle. Liquid, compressed gas, and solid-state storage methods are all promising, but all present technical challenges. GM has demonstrated both liquid and compressed hydrogen storage tanks in our prototype vehicles. We are also doing research on various forms of solid-state storage, such as metal and chemical hydrides. But, given the magnitude of the storage challenge, a significantly expanded federal R&D effort in this area is both necessary and appropriate.

If we are successful in bringing fuel cell vehicles to the market at the beginning of the next decade, the result will be a growing demand for the production of hydrogen. Looking out over a 20-year timeframe, we believe we should begin today to look for better and more sustainable means of producing hydrogen as a vehicle fuel. Like hydrogen storage, we believe this challenge also warrants a significantly expanded federal R&D effort.

As the DOE report correctly points out, cost is another major challenge, but we are making progress in this area, too. GM has achieved a cost improvement with each new generation of our fuel cell stack technology. In addition, we believe that revolutionary vehicle designs like our AUTOnomy concept and Hy-wire prototype—which combine fuel cells, by-wire electronics, and other advanced technologies in new and unique ways—could make fuel cell vehicles much more affordable. These designs enable dramatically fewer vehicle components, a longer-life chassis, and significantly fewer vehicle architectures, all of which have the potential to reduce manufacturing costs.

Since 1988, the computer industry has brought down the cost of computer memory from $17,000 per gigabyte to $6 in 2001—a factor of 3,000 reduction. The cost challenge we face with the fuel cell requires the same type of molecular material breakthroughs, but is an order of magnitude less that what the computer industry had to accomplish. We are confident that we have a really clear definition of the technical milestones and cost targets that we need to meet on each subsystem to achieve total system affordability.

Similarly, we do not think the cost of producing hydrogen will be a "show-stopper." Petroleum companies have said hydrogen can be generated from natural gas at the refinery at a cost that is comparable to conventional fuel costs. Most of the cost of hydrogen comes from the expense of transporting and dispensing it. The good news in this arena is that there is a lot of experience worldwide generating hydrogen and maintaining hydrogen pipeline. Our modeling has indicated that if we used today's technology, we are within a factor of 1.3 of where we need to be on the cost of hydrogen for transportation applications—when compared to U.S. gasoline prices and taking advantage of the inherent energy efficiency of fuel cell vehicles.

The fueling infrastructure is another challenge. But one of the most exciting aspects of hydrogen is that there are many scenarios for producing and delivering it. Hydrogen could be generated at local filling stations as we know them today—with everything up to the storage tank remaining the same. But there is also the potential to refuel at home or at a place of business, using a simple appliance that electrolyzes water. Since the vast majority of homes are already plumbed with water and wired with electricity, it would be very easy to install this new appliance in the garage. A similar situation is possible with natural gas, which is piped into many homes and businesses—a reformer could generate hydrogen from the natural gas.

GM sees distributed generation as a key stepping stone to hydrogen fuel cell vehicles and the early development of hydrogen infrastructure. Last year, we teamed with Hydrogenics, one of our fuel cell partners, to announce our first commercial product—a 25-kilowatt generator designed to keep wireless phone towers operating in the event of an interruption in the power grid. A prototype unit is now being field tested in California. We also announced a 75-kilowatt fuel cell that runs on hydrogen. We recently announced that we will conduct a demonstration of a 75-kW direct hydrogen unit in both the U.S. and Japan. This system is intended for uninterruptible power supply systems, such as hospitals, high-reliability data communications, and to handle peak power demands. We expect to market the unit by 2005. Our intent is to move down the cost curve to enable distributed generation as quickly as possible in order to generate revenues that we can apply to commercializing fuel cell vehicles.

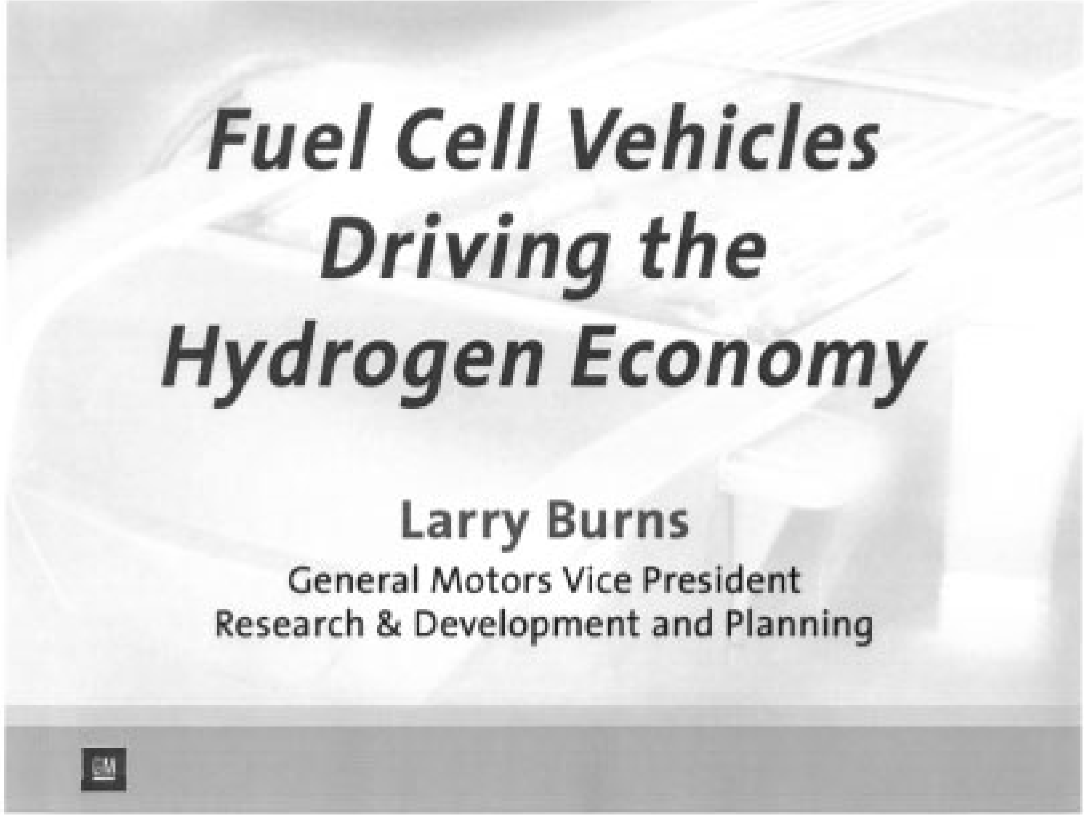
GM has always believed that it will take a three-way partnership involving the auto industry, energy companies, and government to successfully commercialize hydrogen fuel cells for vehicles and stationary applications. We applaud President Bush's new hydrogen initiative and his vision of the hydrogen future, and we would like to see this vision further elevated as a national priority. Specifically, we would welcome a major new national R&D initiative on hydrogen storage and production. In addition to R&D, there are other efforts the Federal Government should take immediately. First, the Department of Transportation should "undeclare" hydrogen as a hazardous material and treat it as a fuel. Second, the government should take the lead on development of a national template for the codes and standards that will be required for hydrogen and fuel cells. Third, every federal agency will have a role in the transition to the hydrogen economy, and they should begin that process today by evaluating the use and impact of hydrogen and fuel cell technologies on their operations.

To this, let me add one caution regarding demonstration projects. We believe that we have much to learn from demonstrations that integrate hydrogen production, stationary fuel cells, vehicle refueling, and fuel cell vehicle production. However, each of these projects is in some way a distraction from our efforts to refine fuel cell technology—particularly on the vehicle side. In the next couple of years, the goal should be to have a limited number of small-scale—but integrated—demo projects to learn about the practical challenges and logistical barriers to an integrated hydrogen economy. Later in this decade, we should expand to some larger-scale demonstrations that begin to enable the hydrogen infrastructure and prepare early customers for the commercialization of fuel cell vehicles.

Within General Motors, the magnitude of our fuel cell investment creates an intense business dilemma—the choice between using our resources to achieve a revolutionary vision. . .or funding the aggressive pursuit of more incrementally focused initiatives. The decisions that we must make in resolving this internal debate will certainly be influenced by the development of a long-term, stable set of governmental policies and initiatives upon which we can properly balance the investment of our finite financial and technical resources.

GM is marching down the cost curve on fuel cell technology and we are confident we will have hydrogen fuel cells that are cost competitive for distributed generation well before 2010. Based on this timetable, we also anticipate that we will be able to make business decisions with respect to the commercial viability of hydrogen fuel cell vehicles well before the 2015 timeframe.

Thank you. I look forward to responding to your questions.



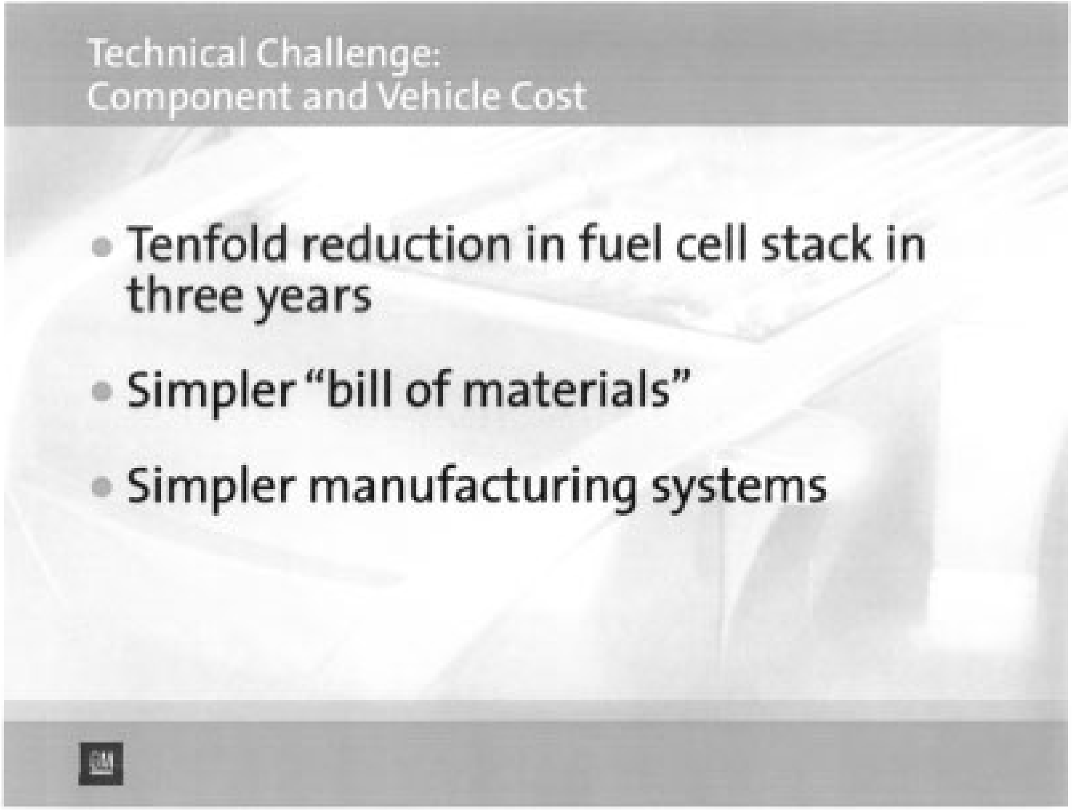
Fuel Cell Vehicles Driving the Hydrogen Economy

Larry Burns

General Motors Vice President
Research & Development and Planning

Technical Challenge: Hydrogen Storage

Infrastructure Requirements

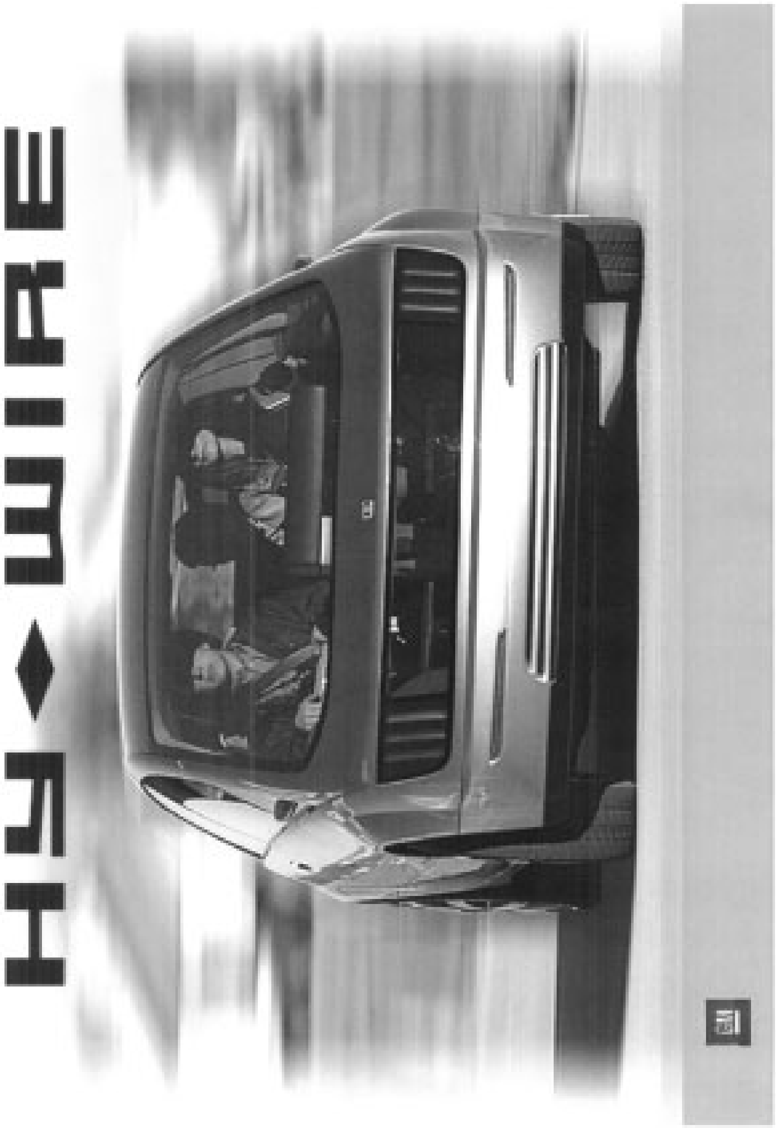


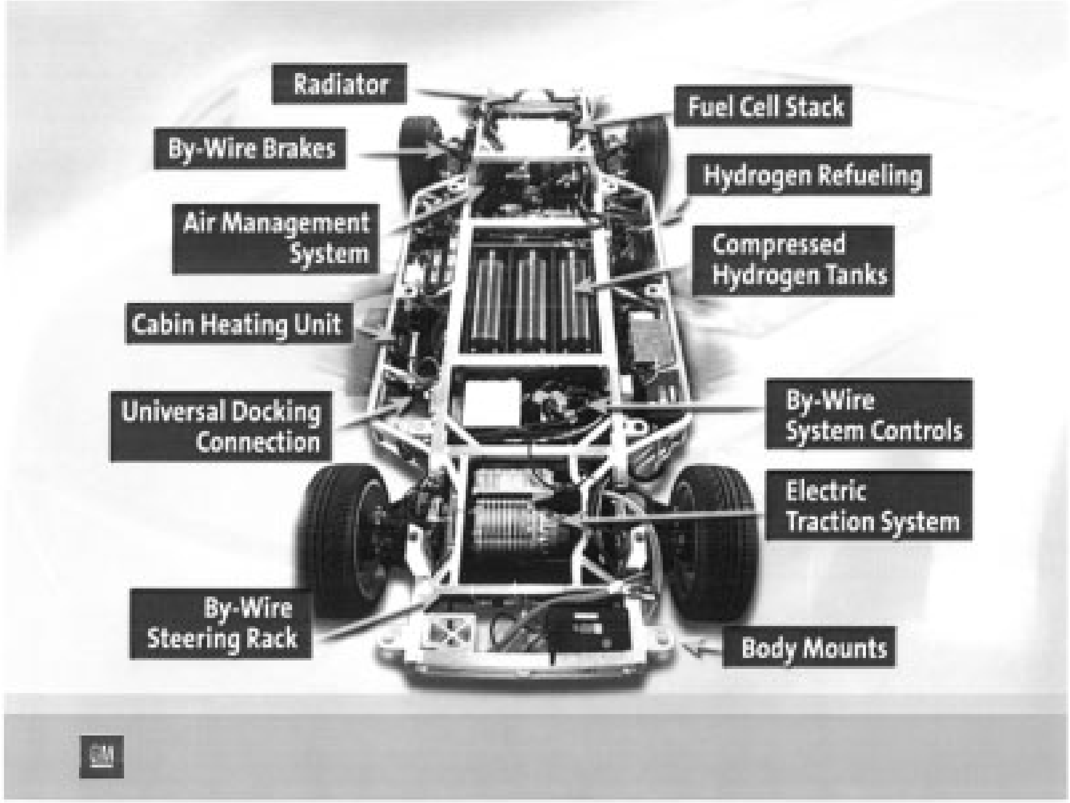
Technical Challenge: Component and Vehicle Cost

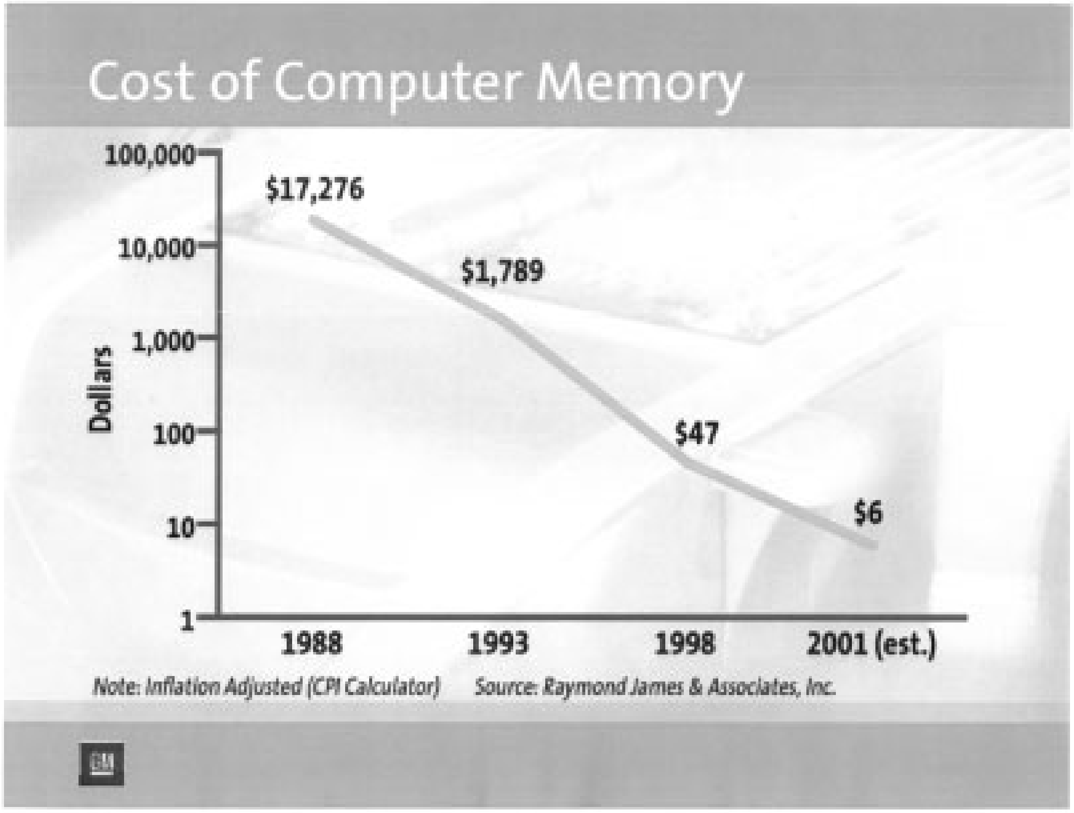
- Tenfold reduction in fuel cell stack in three years
- Simpler "bill of materials"
- Simpler manufacturing systems


AUTONOMY


AUTONOMY
GM

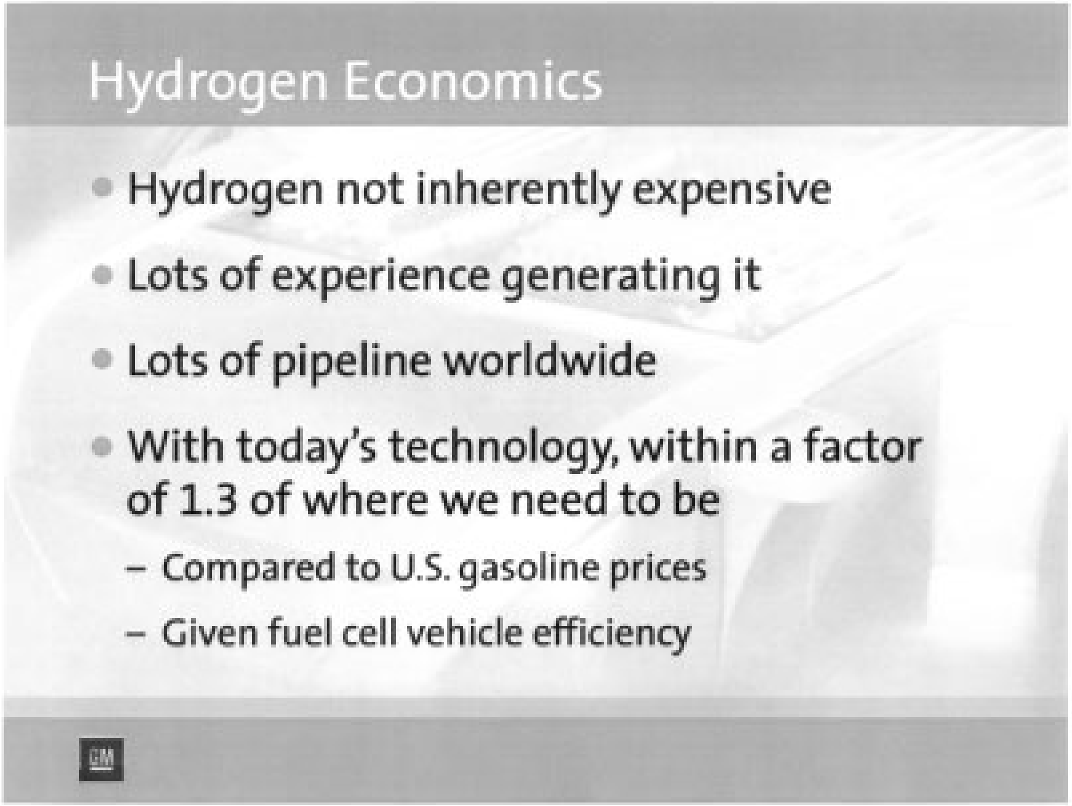

HY◆WIRE
GM


Radiator
Fuel Cell Stack
By-Wire Brakes
Hydrogen Refueling
Air Management System
Compressed Hydrogen Tanks
Cabin Heating Unit
Universal Docking Connection
By-Wire System Controls
Electric Traction System
By-Wire Steering Rack
Body Mounts
GM



Cost of Computer Memory

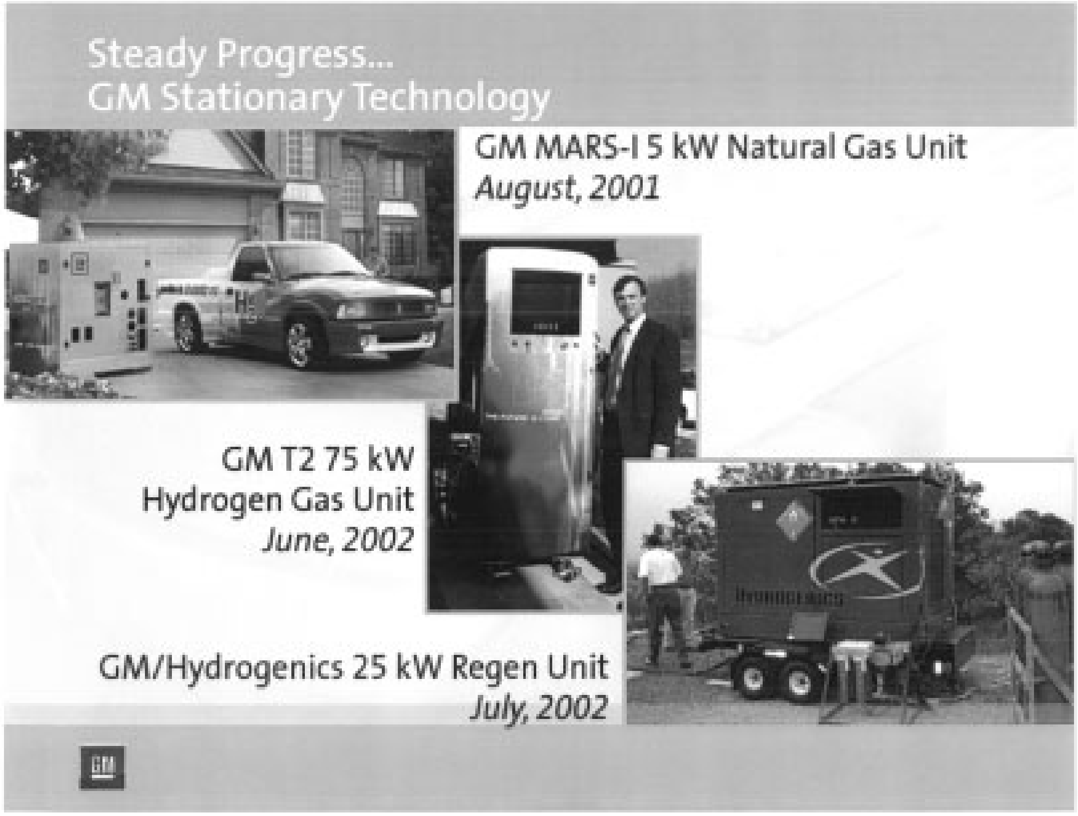
Note: Inflation Adjusted (CPI Calculator) *Source: Raymond James & Associates, Inc.*



Hydrogen Economics

- Hydrogen not inherently expensive
- Lots of experience generating it
- Lots of pipeline worldwide
- With today's technology, within a factor of 1.3 of where we need to be
  - Compared to U.S. gasoline prices
  - Given fuel cell vehicle efficiency

Home Refueling

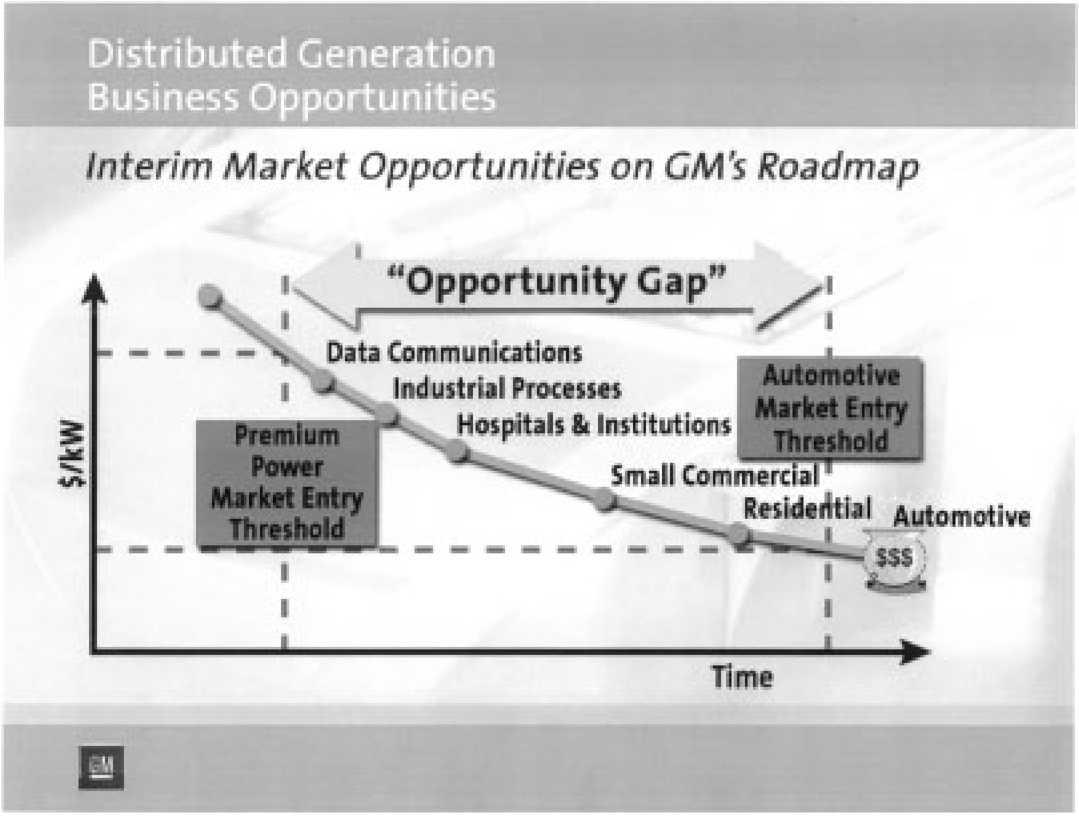


Steady Progress...
GM Stationary Technology

GM MARS-I 5 kW Natural Gas Unit
August, 2001

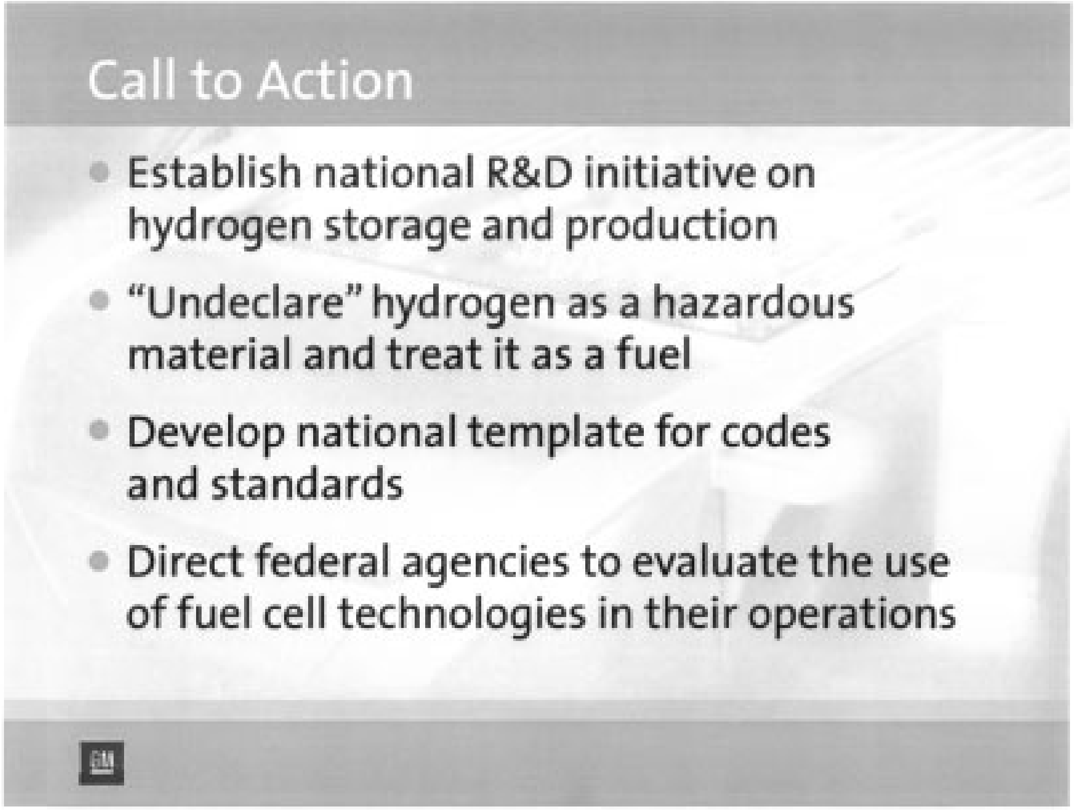
GM T2 75 kW
Hydrogen Gas Unit
June, 2002

GM/Hydrogenics 25 kW Regen Unit
July, 2002



Distributed Generation Business Opportunities

Interim Market Opportunities on GM's Roadmap



Call to Action

- Establish national R&D initiative on hydrogen storage and production
- "Undeclare" hydrogen as a hazardous material and treat it as a fuel
- Develop national template for codes and standards
- Direct federal agencies to evaluate the use of fuel cell technologies in their operations


GM

BIOGRAPHY FOR LAWRENCE D. BURNS

PROFILE

Larry Burns was named Vice President of General Motors Research & Development and Planning in May, 1998. In this post, he oversees GM's advanced technology and innovation programs and also has responsibility for the company's product, capacity, and business plans. He is a member of the Automotive Strategy Board, GM's highest-level management team.

In addition to driving innovation into today's vehicles, Larry is championing GM's "reinvention" of the automobile around promising new technologies like fuel cells and drive-by-wire systems. The goal is to realize sustainable mobility with vehicles that are affordable and aspirational. This is the key to providing the freedom benefits of "automobility" to significantly more of the world's population than the 12 percent who own vehicles today—without compromising future generations.

Larry began his GM career in 1969 as a member of the R&D staff, where his research focused on transportation, logistics, and production systems. He subsequently held executive positions in several GM divisions in the areas of product program management, quality, production control, industrial engineering, and product and business planning.

Larry holds a Ph.D. in civil engineering from the University of California at Berkeley. He also has a Master's degree in engineering/public policy from the University of Michigan and a Bachelor's degree in mechanical engineering from General Motors Institute (now Kettering University).

Larry serves on the boards of the Deafness Research Foundation and the University of Michigan's Center for Hearing Disorders. His interests include running, skiing, backpacking, and spending time with his family. Larry and his wife CeCe have two daughters, Natalee, 15, and Hilary, 11.

Chairman BOEHLERT. Thank you very much. Mr. Huberts.

STATEMENT OF DONALD P.H. HUBERTS, CHIEF EXECUTIVE OFFICER FOR SHELL HYDROGEN

Mr. HUBERTS. Thank you, Mr. Chairman. I am Don Huberts, the Chief Executive Officer of Shell Hydrogen. I appreciate the opportunity to testify before the Science Committee. Shell Hydrogen is the global business division of the Shell Group of Companies. Shell is a global company with operations in over 135 companies. We have a 90 year history in the U.S., and our U.S. assets comprise almost a third of Shells global assets, and reflect all aspects of the energy business, exploration and production, all products, gas and power, chemicals, renewables, and hydrogen. And Shell is the leading retailer of transportation fuels in the U.S.

Shell Hydrogen was established in 1999. We are committed to the commercial development hydrogen energy technologies, including hydrogen storage, reforming fossil fuels, and hydrogen purification. We are active in a number of inaugurative cooperative programs, partnerships, and joint ventures, and I have provided more details on these in my written testimony.

The goal is to meet the future energy needs of our customers and build a sustainable, therefore comfortable, business. With this background, let me turn to the two principle points in my testimony.

First, the future of our energy and hydrogen infrastructure is highly uncertain. A significant hydrogen economy could emerge in 2020 or not until 2050. It depends on complex cycle drivers, what the consumers want, and unpredictable events, as well as on technology breakthroughs.

Shell's views about the future of energy are shaped by scenario work we have been using for years. The scenarios don't predict future events, but they are credible stories about how the future might develop. They look at forces that might push the future. There is a complex interplay between science and technology on the one hand, and social, political and market developments on the other hand. Our recent scenarios look at three key drivers that have the potential to bring fundamental change to the energy system. First of all, what constraints could occur on our global energy resources? Secondly, what changes could occur in peoples' personal preferences, their lifestyle choices, the priorities, the place on environmental concerns; and thirdly, what technology advances could occur that could transform the future. Will existing paradigms be broken, just as the Sony Walkman and mobile phones did?

Shell's most recent scenario work tells two different but compelling stories about the future, based on a different range of assumptions about these three key drivers. But the two stores had important features in common. Natural gas will play a vital role in the next 20 years as a bridge to the future. As new vehicle technologies emerge, there will be pressure on the oil market.

In the long-term, the potential exists for renewable energy sources to be the primary sources of energy if robust energy storage solutions are found. In some looking ahead to the future of hydrogen is highly uncertain because we just don't know what forces will emerge to shape it.

That brings me to my principle point. Governments can play an important play. Governments can stimulate hydrogen technologies and provide incentives. However, governments must do so with a sustained commitment, and now bow in and out. At the same time, governments must allow the markets to work and give consumers the freedom to make commercial choices. Otherwise, money and time is wasted, playing to political choices that turn out not to be commercially the best options. Government policies can make or break projects of technologies; subsidies meant to encourage an industry can sometimes wreck it. Policies have to be intelligent and properly structured, not just well-meant.

Previous experiences with alternative fuels, such as compressed natural gas, show that without prolonged government engagement and strong visible and vocal commitment to deliver a shift in the fuel use in society, these initiatives are destined to fail and remain mesh products.

Policies related to the hydrogen and fuel industries are only now beginning to be formed. It is very important that they are carefully framed and appreciate the challenges. The Federal Government can provide fiscal support and R&D funding, such as the President's recent hydrogen and fuel cell—Hydrogen and FreedomCAR Proposals. Demonstration programs, like that in California, will be critical in moving forward.

Significant work needs to be done in a number of areas, hydrogen production, storage, purification, and other infrastructure related issues. Government and industry working together can provide maximum support.

But let me be clear, technology alone can not bridge the gap in cost of producing hydrogen. Hydrogen is made either from electricity, by spinning water, or it is extracted from natural gas or other fossil fuels. Therefore, the energy in the hydrogen will always be more expensive than that of the sources used to make it. Instead, hydrogen will become competitive due to its other benefits, cleaner air, lower greenhouse gas emissions, to greater efficiency or sequestration, and decreased reliance on foreign energy sources, and improved energy supplies security.

Further, the transition to hydrogen will be a long and capital intensive process. Even with sustained and consistent government support, the huge investment for infrastructure changeover will be required. Industry can only support this if it can be done on a commercial basis.

The initial investment has been estimated by Shell at round 20 billion dollars for the U.S. alone to supply two percent of the cars with hydrogen by 2020, and to make hydrogen available at 25 percent of the existing gasoline retail stations. In the subsequent decades, further buildup of the hydrogen infrastructure will require hundreds of billions of U.S. dollars.

The government can help mitigate some of the risks around such large investments. Ultimately, however, most of the capital will come from the private sector, so it will be consumers that push the effort. The Federal Government should work with industry and other governments to harmonize the international codes and standards. Public/private partnerships can work together to increase public awareness and education. I will be happy to answer any questions.

[The prepared statement of Mr. Huberts follows:]

Prepared Statement of Donald P.H. Huberts

Thank you, Mr. Chairman. I am Don Huberts, the Chief Executive Officer of Shell Hydrogen.[1] I appreciate the opportunity to testify before the Science Committee today to discuss the path to a hydrogen economy—the barriers we face and the opportunities presented in transitioning towards a hydrogen infrastructure.

As the CEO of Shell Hydrogen, I am responsible for leading the development and execution of all the global business activities of the Royal Dutch/Shell Group relating to hydrogen fuel and fuel cells. This includes our activities in hydrogen refueling and fuel cell power generation, and our development of hydrogen generation, storage, and purification technologies. Shell Hydrogen has offices in Houston, Amsterdam, and Tokyo and through its local U.S. affiliate has many activities in the United States. For example, Shell is a founding member of the California Fuel Cell Partnership, of which I was Chairman elect during 2002. Shell is also a sustaining member of the National Hydrogen Association. I will expand on our activities below.

Shell Hydrogen was established in 1999 as a global business division of the Royal Dutch/ Shell Group of Companies (Shell), one of the largest energy companies in the world, with operations in over 135 countries. Shell is the leading retailer of transportation fuels in the U.S. and in many other countries throughout the world. Shell companies in the U.S. comprise 28 percent of the assets of Royal Dutch/Shell; as such, they represent a very important part of the Group's portfolio. Shell companies in the U.S. are involved in all aspects of the energy business—exploration & development, oil products, gas & power, chemicals, renewables, and hydrogen. Our heritage in this country spans more than 90 years, and while you have likely heard a lot during the past ten years about U.S. businesses "going global," we have operated that way for a long, long time. In fact, we are one of the world's first truly multinational companies.

Shell's commitment to sustainable development is demonstrated by our actions. Sir Philip Watts, the Chairman of our Committee of Managing Directors, is the co-chairman of the World Business Council for Sustainable Development. Shell has incorporated the principles of sustainable development into its strategies, operations, processes, budgeting, and training and reward systems. We are developing alter-

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[1] "Shell Hydrogen" refers to a global business consisting of separate companies and other organizational entities within the Royal Dutch/Shell group of companies. Each of the companies of the Royal Dutch/Shell group of companies is an independent entity and has its own separate identity.

native energy sources, such as renewables and hydrogen, which we aim to grow into viable businesses that will meet our customers' future energy needs.

We report annually on our actions to meet our economic, environmental and social responsibilities in our publication *The Shell Report: People, Planet and Profits,* a public document that is available as a booklet or on-line.

Out of this commitment, Shell Hydrogen was established to create business opportunities related to hydrogen energy, including: developing and investing in key technologies for hydrogen storage, reforming fossil fuels, and hydrogen purification; and forming cooperative ventures and partnerships to explore commercially viable approaches to building a hydrogen economy. Shell Hydrogen is committed to the rapid development-to-market application of hydrogen energy technology by bringing together manufacturers, suppliers, distributors, legislators, investors, and consumers. This has led to a number of innovative cooperative programs, partnerships, and joint ventures on an international scale through local affiliates.

California: Shell is cooperating with more than 20 partners from the automotive, energy, fuel cell industries, and government to prepare the path for bringing commercially viable solutions to the densely populated state of California that seeks to improve environmental standards in the face of air-quality problems and increasing energy demands. In West Sacramento, the Partnership has opened a demonstration hydrogen fuel-cell project. A fleet of hydrogen-powered vehicles are serviced at a compressed-hydrogen fuelling station before being operated on local highways.

Iceland: Shell is working as a partner in Icelandic New Energy Ltd. in a pioneering project that involves all phases of developing a hydrogen-based economy. It involves the manufacture of hydrogen and development of a basic hydrogen infrastructure and the study of vehicle performance under real conditions. In the first phase, three hydrogen-powered buses, fuelled by compressed hydrogen made from water, will be introduced, possibly followed by a transition to an entirely hydrogen-driven public transport fleet. The ultimate goal is that all passenger vehicles, trucks, and eventually shipping will be converted by 2030. In addition, the project envisions development of auxiliary markets for smaller fuel cells and bottled hydrogen, and longer-term, bulk exports of hydrogen.

Japan: Shell is involved in a three-year project in Atsugi laboratory to develop a liquid hydrocarbon fuel reformer capable to producing and dispensing hydrogen on the retail forecourt of an existing service station. The R&D effort will use catalytic partial oxidation (CPO) to split hydrogen from gasoline, ensuring that sulphur, carbon and nitrogen are eliminated and leaving only pure hydrogen for fuel-cell use. Another target is increasing the reformer size from the current 50-kW unit to one capable of producing 1,000 kg of hydrogen daily (capable of fuelling 200 cars).

Furthermore, together with Showa Shell Sekiyu K.K., the first hydrogen refueling station will be demonstrated in Tokyo. This is part of the Japan Hydrogen and Fuel Cell Demonstration Project, a program sponsored by the Japanese Ministry of Economy, Trade and Industry to build five hydrogen refueling stations in the Tokyo metropolitan area. The station will provide liquid and compressed hydrogen to a fleet of prototype fuel cell vehicles provided by several automotive companies, which will be used on the city's streets. Showa Shell will operate the station for two years from April 2003.

The Netherlands: In Amsterdam, Shell is involved with the Amsterdam Transport Company (GVB) to test three hydrogen fuel-cell buses for two years as part of the Clean Urban Transport for Europe, or CUTE Project. Currently the Project has fuel-cell demonstration projects in nine European cities and is an initiative of the European Union. Delivery of the first buses is expected in the 3rd quarter 2003, with a hydrogen fuelling installation in place by June. Compressed hydrogen fuel will be produced on site at an installation being developed at the GVB Bus Depot North.

Technology: In addition to these groundbreaking early fueling initiatives, Shell Hydrogen companies invest in technologies that are necessary to enable the hydrogen economy. Shell has been making significant investments in hydrogen production, as our companies are the fourth largest producers of hydrogen in the world, mostly for use in our refineries and chemical plants. The key challenge is to extend hydrogen from being used primarily for industrial purposes to becoming a transportation fuel.

Because distribution costs are high, it is likely that small-scale generation by either natural gas reforming or water electrolysis will occur. Shell is investing in reforming and purification technologies through its affiliates HydrogenSource LLC in Connecticut and QuestAir Inc in Vancouver, Canada, to ensure cheap and clean hydrogen is available when it is needed. Through our experience in these ventures, and with the promise offered by these companies' technologies, we believe that small-scale hydrogen production costs will continue to come down over the next 5–10 years.

Besides reducing the costs of cost of production, new and innovative ways must be developed to store hydrogen. To address this need, Shell and its partners are investing in Hera Hydrogen Storage Systems, which develops solid-state hydrogen storage solutions based on metal- or chemical-hydrides. The aim is to store enough hydrogen in a small space to power many different fuel cell applications. Currently, because hydrogen is such a light, diffuse gas, it is still difficult to store enough hydrogen on board a vehicle to give it adequate range between refueling. Shell intends to sell hydrogen as a fuel for fuel cell cars and other hydrogen-consuming fuel cell applications once the market develops, and our investments in Hera, HydrogenSource and QuestAir support that aim.

The pace of change and the level of research into hydrogen and fuel cells have been accelerating for a number of years. Many of the technologies in existence today hold promise for initial commercial deployment in the coming 3 to 5 years. We consider it likely that PEM fuel cells, which operate at up to 200°F, will be the first to commercialize, initially in portable power units, then for stationary power, and finally for transportation first in fleets, and then from around 2010 in passenger vehicles.

The Path to a Hydrogen Economy

Today I would like to share with you two topics of direct relevance to a hydrogen economy and hydrogen infrastructure:

1. Shell's Scenarios on the future of energy, including hydrogen, to 2050;
2. The role of government in fostering the hydrogen economy.

The most important points I want you take away from my testimony are:

1. The future of our energy and hydrogen infrastructures is highly uncertain. A significant hydrogen economy may emerge by 2020 or not until 2050, depending as much on complex societal drivers and unpredictable disruptive events, as on technology breakthroughs.
2. Governments can play an important part in stimulating development of the necessary hydrogen related technologies and providing encouraging incentives during the early stages. The sustained political will of the U.S. Government is particularly important in this regard. However, governments must allow the markets and consumers the freedom to make the fundamental commercial choices. Otherwise, money and time is wasted clinging to political choices that turn out not to be commercially the best options.

Shell Scenarios

Shell's views about the future of energy are shaped by scenarios that look out to 2050 in terms of energy needs, possibilities, and choices. We've been using scenarios for 30 years to help us think about the future. Scenarios are not predictions. Rather, they are ways of challenging assumptions, encouraging debate, and exploring possibilities. They are tools for focusing on critical uncertainties—the unexpected discontinuities or unknown possibilities that could transform our business environment. Our scenarios don't pinpoint future events; rather, they consider the forces that might push the future along a different path.

Scenarios are credible, relevant and challenging alternative stories about how things might develop. Credibility is essential. We harness our experience in energy businesses and technology development—as well as a wide range of outsider expertise—to develop them. What I will tell you today comes from our most recent work in this area: "Energy Needs, Choices and Possibilities—Scenarios to 2050."

Let me say before I begin that I fully understand that this House Science Committee is particularly interested in hydrogen fuels for transportation. Our scenario work includes transport, of course, but it is not confined to this sector, as important as it is. Because of the interrelationships and uncertainties associated with all energy sectors, Shell has taken a "holistic" approach to looking at the future.

What questions do our long-term energy scenarios attempt to answer?

First, there is an overarching question about the ability of a dynamic energy system to respond to the threat of climate change in this half-century.

Other key questions explored in the scenarios include:

> When will oil and gas resources fail to meet rising demand? What will replace oil, particularly in transport?

Who will drive the expansion of renewables? How will energy storage for renewables like solar and wind be solved?

How might a hydrogen infrastructure develop?

How will the choices of consumers and citizens affect energy paths?

We looked at important influences that are likely to shape the future of energy, including demography, urbanization, income and market liberalization. And, we looked at three critical drivers that have the potential to bring about fundamental changes in the energy system—resource constraints, technology development and changing social and personal priorities.

A word or two about global resource constraints: Some people see impending limitations on the ability of fossil fuel resources to continue meeting growth in energy demand. We think scarcity of oil supplies is unlikely before 2025, and could be delayed even longer. Natural gas resources are much more uncertain. Scarcity could occur as early as 2025, or well after 2050. The more immediate issue is whether we can develop the infrastructure to deliver remote gas economically.

There is no shortage of coal, but resources are concentrated in a few countries and are becoming increasingly costly to exploit, among other reasons, due to tightening emission standards. Renewable resources, like solar and wind, will compete with food and leisure for land use and require new forms of energy storage. Technological advances are at the core of the transition to new forms of energy. These advances offer superior or new qualities—often transforming lifestyles as well as energy supplies.

In the long-term, two potentially transforming energy technologies are:

Solar photovoltaics, which offer the possibility of abundant direct and widely distributed energy, and

Hydrogen fuel cells, which offer the possibility of high performance and clean energy from a variety of fuels.

Both are in the early stages of development and face large challenges. Energy storage is the fundamental problem. Both still have a long way to go on affordability, although they will benefit from manufacturing economies.

People's choices also affect energy development in two ways—by their personal preferences as consumers and their priorities as citizens. Personal lifestyle choices and consumption patterns drive the energy system. These forces operate within frameworks shaped by social attitudes and concerns, such as energy security, air quality and the climate change.

Now about the scenarios we've developed to the year 2050. There is no limit, of course, as to how many we could generate about the future. But our experience is that we can better engage people by limiting our thinking to two focused and thought-provoking scenarios. They are called *Dynamics as Usual* and the *Spirit of the Coming Age.* I'll talk briefly about both of them.

Dynamics as Usual focuses on the *choices that people make about clean, secure and increasingly sustainable energy* that—with growing resource scarcities—drive the evolution toward renewable sources. However, this transition is anything but smooth and reflects intense competition among priorities and technologies. *Dynamics as Usual* explores the continuation of the dynamic which has shaped the evolution of energy toward lower-carbon fuels—with electricity as the carrier—in response to demands for cleaner, more convenient energy.

Spirit of the Coming Age focuses on the energy *choices made by consumers in response to revolutionary new technologies*—which arise from unexpected sources—and transform the system.

The two scenarios reflect differences in energy resources, timing and nature of technology development and social and personal priorities. However, the scenarios also have important common features, including:

- the vital role of natural gas as a bridging fuel during at least the next two decades;
- pressure on the oil market as new vehicle technologies diffuse;
- the shift towards distributed heat and power supply for economic and social reasons, and
- in the long-term, the potential for renewables to be the eventual primary source of energy if robust energy storage solutions are found.

Dynamics as Usual

Let me focus on the four main elements of *Dynamics as Usual:*

1. existing technologies respond,
2. the 'dash for gas,'
3. renewables boom and bust, and
4. the oil transition and renewables renaissance.

Let's consider each of these points in turn.

First, existing technologies respond. The demand for clean, secure and sustainable energy stimulates a drive for energy efficiency within existing technologies, particularly the internal combustion engine. Advanced internal combustion and hybrid engines deliver the same performance as standard vehicles—but use as little as half of the fuel. Fueling inconvenience limits the appeal of fuel cell vehicles.

The spread of high-efficiency vehicles disrupts oil markets. Prices are depressed until firmed by growing developing country demand for transport and heating fuels after 2015. Oil consumption grows steadily—but weakly—for 25 more years.

Second, the dash for gas. Natural gas use expands rapidly early in the century—reflecting its economic and environmental advantages in liberalized markets. Where gas is available it fuels most new power generation and accounts for three-quarters of incremental OECD capacity up to 2015. Older coal plants cannot meet tightening emissions standards and are increasingly replaced by gas.

The rising costs and logistical complexity of expanding coal deliveries from northern mines prompts China to embark on major gas import projects. Pan-Asian and Latin American gas grids emerge. Large-scale LNG trade is increasingly competitive. By 2020 gas is challenging oil as the dominant source of primary energy. However, expansion thereafter is constrained by concerns for security of supply.

New nuclear plants have trouble competing in deregulated markets. Most existing nuclear capacity is maintained, but nuclear steadily loses market share in OECD countries.

Third, the renewables boom and bust. Strong government support in OECD countries enables renewable energy to grow rapidly for two decades through established electricity grids. The cost of wind energy continues to fall as turbines exceed 3 MW.

By 2020 a wide variety of renewable sources is supplying a fifth of electricity in many OECD markets. Then growth stalls.

Limited electricity growth constrains expansion in OECD countries and with little progress on energy storage, concerns about power grid reliability block further growth of wind and solar. In developing countries, renewables do not fully compete with low-cost conventional resources.

As renewables stagnate and gas security concerns grow, it is not clear what will fuel future energy supplies.

It is a decade of great energy policy dilemmas.

Fourth and lastly, the oil transition and renewables renaissance. Around 2040, as oil becomes scarce, advances in biotechnology together with vastly improved vehicle efficiency allow a relatively smooth transition to liquid biofuels or Fischer-Tropsch fuels. The existing transportation system can be modified at low cost.

A new generation of renewable technologies emerge. The most important is organic and thin film embedded solar materials. New ways of storing and utilizing distributed solar energy are developed.

By 2050 renewables reach a third of world primary energy and are supplying most incremental energy.

Spirit of the Coming Age

Now let me turn to three key elements of the second scenario, *Spirit of the Coming Age:*

1. breaking paradigms,
2. the ubiquitous fuel cell,
3. the hydrogen economy.

Let's talk about breaking paradigms.

The Sony Walkman was repeatedly dismissed by focus groups. Portable computers and mobile phones are examples of innovations that broke existing paradigms. Such developments often come from niche market fringes—ignored by incumbent suppliers—where physical constraints force innovation and consumers are willing to pay a premium.

In this scenario technological development is rapid and—critically—societies adopt new technologies more or less immediately. With abundant gas supplies, innovations push fuel cells into a variety of new applications. The outlook is bright.

By 2015, installations of both stationary and mobile fuel cells have won broad public acceptance. After all there are already hundreds of installations in place in the U.S. and in highly environmentally conscious Germany. This scenario says that by the end of the decade there is growing enthusiasm for the technology.

Automobiles manufacturers know that hydrogen fuel cell vehicles match the public mood because they are cleaner, quieter and offer high performance. They can also support more electrical services—digital communications, pre-entry heating and cooling, and in-car entertainment—which consumers want but which require too much power for many traditional engines. The constraint is the fuel infrastructure and the potential health hazards of alternative fuels.

Demand for stationary fuel cells—for businesses willing to pay a premium to ensure highly reliable power—helps drive fuel cell system costs down. This provides a platform for transport uses, stimulating further cost reductions—well below conventional power and heat technologies.

In this scenario, by 2025 a quarter of the OECD vehicle fleet uses fuel cells. The global automobile industry rapidly consolidates around the new platform. Technical advances in transport and power services feed off each other, solving mutual problems. Fuel cells also benefit from broader developments in material technology.

Cars no longer need to be idle for 95 percent of the time. Through docking stations, they can provide energy to homes and buildings.

Now, let's talk about the emergence of a hydrogen economy. The advantages of the new technology push the transition to hydrogen well before oil becomes scarce. The higher the demand for fuel cells, the less oil fetches. Renewable energy makes steady but unspectacular progress until 2025. "Green energy" niches remain small in most regions.

After 2025 the growing use of fuel cells for heat and power creates a rapidly expanding demand for hydrogen. It is widely produced from coal, oil and gas fields, with carbon dioxide extracted and sequestered at source. By 2050 a fifth of carbon dioxide emissions from the production and use of energy are being sequestered.

Large-scale renewable and nuclear energy schemes to produce hydrogen by electrolysis start to become attractive after 2030. Renewable energy becomes a bulk supply business and starts to expand rapidly. Hydrogen is transported in gas grids until demand justifies dedicated hydrogen pipelines.

A century-long process of hydrogen infrastructure development begins. The need for sequestration peaks after 2050 although only a small part of the total sequestration capacity has been used. It all sounds very positive. Still, it is worth noting that even in this most optimistic scenario for hydrogen it takes another 40 years before hydrocarbons fully lose their dominance of the energy industry.

What I've just given you is an overview of our two long-term energy scenarios. They both underscore the complex interplay between scientific and technical advances and social, political and market developments. They also underscore the inherent uncertainty on the timing and nature of the hydrogen economy.

Role of Government

Shell has extensive experience with government influence around the world, as no other industry is subject to so many policies and such political control. We know that policies can make or break projects, technologies and even whole industries. We have also learned that subsidies meant to encourage an industry can sometimes wreck it. We've learned that policies have to be intelligent and properly structured, not just well meant.

Policies related to the hydrogen and fuel cell industries are only now beginning to be formed. It is very important that the right principles are ingrained in these policies and that they are carefully framed.

This must be based on an appreciation for the challenges in producing hydrogen. Hydrogen is made either from electricity by splitting water, or extracted from natural gas or other fossil sources. Therefore, the energy in the hydrogen will always be more expensive than that of the sources used to make it. Hence, competitiveness must come from the additional benefits produced in cleaner air, lower CO_2 emissions through greater efficiency or sequestration, and improved energy supply security. These externalities need to be reflected in price signals received by the market, otherwise technology alone cannot bridge the gap in cost. The incumbent petroleum based technology already has an infrastructure in place and is made from a relatively low cost feedstock. Hydrogen can only compete in the early years with the involvement and consistent support of government.

Our participation in the California Fuel Cell Partnership has provided valuable insight into the potential social benefits resulting from the use of fuel cells, and the hurdles for implementation of a hydrogen infrastructure. Through working in partnership with car manufacturers, Federal and State government agencies, and other energy companies, we have researched pathways for a transition to a hydrogen economy in California. Such cooperation is unique and essential to ensure a hydrogen transition becomes feasible.

The Federal Government has a key role to play in setting up the playing field for private enterprise to compete. Previous experiences with alternative fuels such as compressed natural gas (CNG) show that without prolonged government engagement and strong, visible and vocal commitment to deliver a shift in the fuel used in society, these initiatives are destined to fail and remain niche products. In addition to the sort of fiscal support and R&D funding proposed in the President's recent Hydrogen Fuel and FreedomCAR initiatives, the government should also work towards harmonized international codes and standards, increasing levels of public education, and mitigating the risk of in developing a new fuel infrastructure. Finally, as I pointed out earlier, it should ensure that the integral social, environmental, and economic costs and benefits to society of any fuel are properly considered by the market.

The transition to hydrogen will be a long and capital intensive process, and will need a sustained political will to realize the significant benefits of cleaner air, lower greenhouse gas emissions, and a decreased reliance on foreign energy sources. Many of the existing technical and cost hurdles can be overcome with sustained and consistent government support, but even so the huge investment for the infrastructure changeover can only be supported by industry if it can be done on a commercial basis. The initial investment has been estimated by Shell at around USD 20bn for the U.S. alone, to supply two percent of the cars with hydrogen by 2020 and to make hydrogen available at 25 percent of the existing gasoline retail stations. In the subsequent decades, further build-up of the hydrogen infrastructure will require hundreds of billions of U.S. dollars. Support from the government in mitigating some of the risks around such large investments will clearly be indispensable. However, if the hydrogen sector is to truly take off, most of the capital will come from the private sector. Therefore, it will be consumers, and by extension, the capital markets that will ultimately determine how much money flows into this new industry.

I hope that I have convinced you that Shell believes in hydrogen and is putting its money on the table. Through the companies of Shell Hydrogen, we are already a significant investor and we are willing to invest further as opportunities arise. Shell believes that governments should promote research and development—and provide significant funding—but, that they should do so in a way that allows for innovation and competition in the marketplace, and provides customer with a choice.

I would be happy to answer any questions.

BIOGRAPHY FOR DONALD P.H. HUBERTS

Chief Executive Officer

Don Huberts has a Master's Degree in Chemical Engineering from Delft University of Technology, and a Master's of Science of Management (MBA) from the Sloan School of Management at the Massachusetts Institute of Technology in Boston, MA, USA. He joined Shell in 1980 as an assistant development engineer in Catalytic Cracking. Subsequently Don worked in Process Control in Houston, TX, USA and in Refinery Operations in The Netherlands. After obtaining his MBA at MIT in 1992, he worked as country focal point for Japan and the Philippines in the regional organization based in London, which was followed by an assignment as personnel resourcing adviser in The Hague. Thereafter, he was General Manager of a crude oil refining and product importation joint venture company in the Dominican Republic.

In Hydrogen Don is responsible for developing Shell's global business in the emerging hydrogen and fuel cell industry. He was the 2002 Chairman of the California Fuel Cell Partnership. Don is Chairman of the Board of HydrogenSource, a joint venture between UTC Fuel Cells and Shell Hydrogen. He is also member of the International Advisory Board of Conduit, a European based venture capital company which focuses purely upon fuel cells and related hydrogen technologies.

Don is married and has three young daughters. He enjoys spending time with his family, soccer, movies, theater and visiting interesting places.

DISCUSSION

INDUSTRY'S OPINION ON GOVERNMENT POLICY OPTIONS

Chairman BOEHLERT. Thank you very much. Let me start with our two witnesses from industry, Dr. Burns and Mr. Huberts. To what extent do industry's plans and assumptions about making money from your hydrogen investments depend on specific government policy options, whether they are incentives or regulations? And can we get to a hydrogen economy just relying on narrowly defined market forces? Dr. Burns.

Dr. BURNS. I believe there is tremendous business growth opportunities for companies like General Motors and Shell associated with hydrogen. The reason we are so excited about this technology is we truly believe we can make better cars and trucks around the technologies that are emerging at this point in time. But if we have those cars and trucks available, and the hydrogen is not available, we are not going to be able to accomplish our own goals because the customers wouldn't have the hydrogen conveniently there. So we believe the governments can play a very important role in a couple of ways.

First of all, to help keep hydrogen on an equal playing field with the cost of gasoline, recognizing that infrastructure for gasoline has been evolving over 100 years, where hydrogen will not just be starting out. So we need some mechanism to make sure that hydrogen has an opportunity to compete on a level playing field for a period of time to kick this off.

Codes and standards also will be real important. And we need the R&D funds, we believe, to lead to some more important breakthroughs on materials to make these technologies more affordable in the near-term.

Chairman BOEHLERT. Mr. Huberts?

Mr. HUBERTS. Mr. Chairman, as I said, the externalities, as also Dr. Ogden pointed to, are key to realizing the benefits of hydrogen, and therefore, government policy will be required to assure that hydrogen receives the benefits of those externalities.

Chairman BOEHLERT. Mr. Lloyd, would you have a comment on this question?

Dr. LLOYD. With respect to—I think, again, speaking on behalf of the Partnership here, clearly we are hoping that working as partners here; we can develop a mechanism whereby we can get these vehicles on the road. I would say very carefully in my other hat, I will say that what we have found over the years that it is good to have basically a carrot on a stick. One of the things that we found just reading in the Financial Times yesterday, that the market share for the Japanese companies is increasing in the U.S. That is a time when, in fact, they are also developing. They have hybrids on the road. They are selling hybrids. They have fuel cells in limited numbers on the road in California. What that indicates to me is that they have got the right mix of being able to push the technology, respond to some of the stimuli, and yet they are gaining market share. I can't—I will completely agree with Dr. Burns. We—and we have learned this that, in fact, you have to build something the public will buy. I think maybe the Japanese have got a model that seems that they are getting both, advancing technology and——

Chairman BOEHLERT. Would they mix with the hybrids and the fuel cell?

Dr. LLOYD. Well, by the fuel cell, it is very early, but obviously they are getting those very small numbers on the road, the same as GM is doing there. But I think if you look at the hybrids, now in fact while it is difficult for the U.S. population to buy hybrids from the domestic manufactures, you have got Honda and Toyota who have already invested in hybrids. Obviously, there is significant cost in electric drive, and the public is obviously responding with sales. And if you look across the board, the fact that they are gaining market share tells you that, obviously, they are being able to push the technology, put vehicles out there which may be more costly, but the public does seem to be responding.

Chairman BOEHLERT. Dr. Ogden.

Dr. OGDEN. I think that recognition of externalities is going to be an important condition for bringing about a hydrogen economy. I see this happening both in terms of policies to recognize those, and also in terms of changing consumer preferences really, for vehicles that would offer diverse energy supply, and lower emissions of air pollutants and greenhouse gases. So I see this as really taking place as a paradigm shift, and I think the government has an important role to play there in encouraging the progress toward that kind of future. And having a societal debate really about whether that is the sort of thing we want to do, you know? Opening it up and bring——

DOE'S OPINIONS ON GOVERNMENT POLICY OPTIONS

Chairman BOEHLERT. Mr. Garman, you heard him. Everyone seems to be saying we need policy tools; we need to take externalities into account. What is DOE doing about this?

Mr. GARMAN. Actually, well, you have got to get the technology in the ballpark before you get close to being able to play in terms of addressing the externalities. In a case in point, for instance, it might be wind energy. I mean the Department, through its R&D program, has brought down the cost of wind energy from 10 to 20 cents a kilowatt hour where no conceivable tax incentive or other policy mechanism would make it competitive. But technology work brought the cost of wind technology down to four to six cents a kilowatt hour, in the most, you know; class six wind areas, productive areas, which means you suddenly can begin to play with a production tax credit or some other government mechanism to incentivize use of the technology. So I think it is important that before we get too hung up on what kind of market mechanisms or tax incentives, or other mechanisms we might want to use, that we get the technology in the ballpark, because the revenue impacts of fuel cell incentives or other mechanisms like that would just be budget breakers. We have got to get the technology close. And when we get into the ballpark, then I think we can have a good productive dialogue about the additional mechanisms that might be needed.

SOURCES OF FUNDING FOR THE HYDROGEN INITIATIVE

Chairman BOEHLERT. I can't escape noting that one of the ways you intend to pay for the fuel cell initiative—hydrogen initiative is cutting wind energy R&D?.

Mr. GARMAN. I hoped you would give me the opportunity to respond to that, Mr. Chairman.

Chairman BOEHLERT. I will give you that opportunity right this moment.

Mr. GARMAN. Because in truth, our wind request for 2004, we were—of course had to make our request before we had the 2003 appropriates in hand. But the 2003 appropriations was 33 million for wind; our request for 2004 is 41.6. Reasonably flat, our hydro is actually up, the geo-thermal reasonably flat, solar is from 87 to 79, but notable tag subset of that is actually up a little bit. We did take a hit in biomass, but actually when you look at even our biomass number, our request when you take away the Congressional earmarks that may or may not contribute to the R&D goals, we are actually asking for more than we asked for biomass on our core R&D goals. So we have a very strong—and in fact, in the overall energy supply account for our renewable energy, we actually—our 2004 request is actually up over the 2003 appropriation, 444 million to 426 million. So we have a strong renewable energy R&D request. We—a lot of the plus up that you see in the overall account is due to the additional dollars that we are asking for in hydrogen that is funded also from this account, on some of the very R&D goals that Dr. Burns was saying we needed to pay attention to.

Chairman BOEHLERT. It proves the point that different people can look at the same figures and interpret them in a different manner. The new Chair of the Subcommittee on Energy, Ms. Biggert.

ROLE OF PARTNERSHIPS IN THE HYDROGEN INITIATIVE

Ms. BIGGERT. Thank you, Mr. Chairman. I have got a question for Mr. Garman. In your testimony you gave some details about the focus and structure of the President's Hydrogen Initiative, and thank you for that, but I think there is still some basic questions that haven't been answered. We don't know, for example, who will be the partners with this—for this—with the program, or even who will perform the research. In other words, what will be the role of the national labs? What about the oil—energy companies? Are there specific companies that you are looking in to partner with, and if so, which ones? And when are we going to see this plan?

Mr. GARMAN. Excellent, thank you for that question. We have begun discussions with a variety of energy companies. We are looking particularly at those energy companies that have a sizeable investment in hydrogen work already. Fortunately, a lot of energy companies do that. They are the producers of a large amount of hydrogen, some nine million metric tons we produce each year, mainly for petroleum refining applications. We have been working with our FreedomCAR partners on a charter, and we have been discussing with a variety of energy companies possible participation. We hope that we can approach those companies in—just within a few short weeks and engage them very actively.

In terms of the research and who will do it, we try to ensure that the research is undertaken on a competitive and peer-reviewed basis. Our—if FreedomCAR and the PNGV prior to that is a model, most of the research is actually performed—the largest percentage is done in the national labs, and then following close behind that are tier one and tier two automobile suppliers. Ironically, the big three get very little, if any, of the dollars, and I think that if that model holds, you will see the R&D mainly being born by national labs and suppliers to the energy company, those who actually make hydrogen compressors, reformers, and other types of equipment.

ROLE OF THE OFFICE OF SCIENCE IN THE HYDROGEN INITIATIVE

Ms. BIGGERT. If you use the labs and the basic research, how about the Office of Science, are they involved? And right now we are seeing very flat funding of the Office of Science, will there be increased funding for this or will other—they will have to drop other basic research items?

Mr. GARMAN. We—Science is already doing a superb job working with us. We have created an internal posture plan, which is under policy review now. We hope to share that with the Committee in the months ahead. Science is a strong partner with us in developing the plan on how DOE as an entity is going to pursue these things. They are already doing cutting edge research. Their Biological and Environment Research Division is working on microbial generation of hydrogen that looks quite promising. The Basic Energy Science Program has been helping us and working on materials for the storage of hydrogen, which you heard Dr. Burns say was a critical technology on board the vehicle. Science is very well integrated with our work. We think that they—we view them as a strong partner. I don't see—I think they will receive very lavish resources to do this work.

Ms. BIGGERT. So there will be other resources that will be available other than what they received for Fiscal Year 2003 and what is proposed for 2004?

Mr. GARMAN. Yes, sir. The—yes, ma'am. The President has provided us with a funding profile. The 1.2 billion that includes 720 million dollars of new funding, and this would be shared between—my office would get the bulk of the funding, but Science would get some as well, as would Fossil and Nuclear Energy inside the Department.

Ms. BIGGERT. Would that plan—is that part of the Initiative that you talked about—the plan for the Hydrogen Initiative? Is there another plan for what the government will be doing or is this all one plan that we will be receiving?

Mr. GARMAN. Our posture plan is really—the simplest way to think about it is the DOE response to the President's Initiative, and how my Office of Energy Efficiency and Renewable Energy—the work, the hydrogen work that is being undertaken, the Fossil Office, the Nuclear Office, the Office of Science, will be integrated to make sure that we are hitting the R&D objectives.

Ms. BIGGERT. Thank you very much. Thank you, Mr. Chairman.

Chairman BOEHLERT. Thank you, Mr. Lampson.

SAFETY CONCERNS AND PRECAUTIONS FOR HYDROGEN USAGE

Mr. LAMPSON. Thank you, Mr. Chairman. We have been using hydrogen for a long time, as on the Space Shuttle and Space Station, and lots of other places, but generally today, it is handled by trained persons under controlled conditions, and it is clear that we have the knowledge and experience to handle these quantities safely under the conditions that were set out. But if hydrogen is to become widely available to people who don't understand how to handle it, it seems to me that a whole panoply of problems need to be solved. And let me ask some of those, and I am going to call Mr. Huberts and see if he will help me understand them. Hydrogen, I understand burns with an almost invisible flame. People could literally walk into it unknowingly. Hydrogen is highly ignitable. The ignition characteristics differ from natural gas, and how do they do so? What conditions, what precautions might we be able to take? How easily is it ignited by static electricity? What precautions might we be able to take? And also, unlike natural gas, hydrogen rises when it is released into the atmosphere. What special considerations need to be taken into consideration when handling in enclosed areas? Can you talk to me about those for a minute, please?

Mr. HUBERT. Sure, as we are going through the learning process right now, one of the examples is the station that will be opening here in the DC area. We will address those aspects under real-life conditions. So there will be changes, for example, in the way in which the station is designed in order to be safe, recognizing that hydrogen goes up instead of going down, contrary to different fuels, recognizing that it a gas, not a liquid. So those different properties of hydrogen need to be managed in a different way.

We believe that can be done safely, and what is happening right now in demonstration projects that are taking place in these years is testing all those things out in practice, and getting the design rules established, getting the codes and standards established under which this new fuel can be handled safely by the general public.

So your point is very valid. There is also a role there for the Federal Government in helping to harmonize these codes and standards as they are developed to make sure that the Fire Marshals, who are the local authorities, giving permits for refill stations, they know how to handle this fuel. And this is a whole process that is going to take several years, and the demonstration projects are really a key part of that process.

Mr. LAMPSON. Do you envision ultimately that the general public would be able to pull up to a gas pump similar to what we do today and pump up with hydrogen?

Mr. HUBERTS. Yes, definitely.

Mr. LAMPSON. Assuming that hydrogen has to be transported, do we have the experience with hydrogen pipelines? Will the gas have to be compressed to be shipped? Will the stresses and metal fatigue be similar to natural gas or oil pipelines, and how will the dangers of hydrogen pipelines compare to natural pipelines? Are they more likely to be terrorist targets?

Mr. HUBERTS. Hydrogen pipelines are available today, and there are hundreds of miles of hydrogen pipelines across the country. For instance, in the Texas area there is a little experience with those kind of pipelines. They are not exactly the same as natural gas pipelines. One has to take into account the different properties of hydrogen in designing these pipelines, but the experience to do that is available, and these pipelines have been operated safely for many, many years.

As far as transporting hydrogen on the road, it is transported routinely, has been transported routinely for many years in tanker trucks in liquid form, in gaseous form. So, we will—hydrogen is different than natural gas in some aspects, the experience in transporting it is available, and we will make use to that experience and build on that

COST OF HYDROGEN VS. NATURAL GAS PIPELINES

Mr. LAMPSON. How about the cost?

Mr. HUBERTS. Hydrogen pipelines are more expensive than natural gas pipelines, and that is one of the factors. As I explained, hydrogen is more expensive than other forms of energy because it has to be made, and it has different properties. So the benefits of hydrogen have to come from its greater efficiency, from social benefits, but at the end of the day it is going to be more expensive a hydrogen pipeline than it is to build a natural gas pipeline. It is—that is simply a fact.

Mr. LAMPSON. Thank you very much. Mr. Chairman, I have got more questions, but I see that little yellow light out there, and if I start the next one you are going to jump on me. So I will give you back my time and ask for a second round.

Chairman BOEHLERT. We will have a second round, Mr. Smith.

DIRECTION OF HYDROGEN RESEARCH EFFORTS

Mr. SMITH. Thank you, Mr. Chairman. Certainly hydrogen is abundant. I just am a little concerned that we might start running top speed that might be the wrong direction. Is it your impression that we are going to do the additional research effort in the hydrogen fuel cells that might mean a sacrifice of some of our other efforts, whether it is the traditional—whether it is some of the hybrid cars, whether it is additional research efforts in developing different, more efficient batteries, or better, more-efficient conventional engines? Or Toyota I understand is coming out with a vehicle that can get 100 miles per gallon? Maybe Dr. Burns, a question to you as I add to the questions, my interest probably would be two-fold—or our interest in general should be two-fold, and one is to reduce our dependency on imported petroleum energy, and the second is to have the kind of production of vehicles in the United States that is going to allow us to have the jobs in the economy, if you will. And Japan seems to have taken a lead. General Motors was going very strongly in the electric car, and I guess you still have an electric car research effort that has sort of faded out, whether it was the battery, the inability to develop batteries or etcetera. So the bottom line question, will the big three in the United States be at the forefront in the development of new and better, more-efficient vehicles, regardless of whether it is hydrogen cells or something else?

Dr. BURNS. That is a very important question, Congressman. General Motors has a near-term, midterm, and long-term view on propulsion technologies. In the near-term, improving the internal combustion engine, both gas and diesel, improving our transmissions are critically important. My role as head of R&D and Planning is—requires me to have the right balance portfolio of research projects within our company that allows us to improve the existing cars as we know them, as well as prepare ourselves for the longer term future. One technology we are especially excited about that will be utilized with our eight cylinder engines on our large sport utility engines and pick-up trucks is called displacement on demand. This is a technology that allows you to literally shut down four of the eight cylinders once the vehicle has been accelerated, to realize efficiency gains and emission advantages. And that can result in anywhere from a five to eight percent economy improvement. We coupling that technology with hybrid technologies for those same trucks. The hybrid system combined with displaced on demand is an opportunity to improve fuel economy on the order of 20 percent for these vehicles.

IMPORTANCE OF HYBRIDS AS AN INTERMEDIATE STEP TO FUEL CELL VEHICLES

We see hybrids as an important intermediate type of a technology. Fuel cell vehicles likely will be hybrid vehicles as well. By that I mean they will have some type of a battery system on them, or capacitor system to store the energy associated with slowing the vehicle down and breaking the vehicle.

Mr. SMITH. The *New York Times* suggests that GM is coming—and I guess your plan is to come by May or the summer with five minivans or a certain number, why are you doing that?

Dr. BURNS. Yeah, that is correct. The six vehicles that we are going to have available as part of the demonstration with Shell in Washington DC; they are pure full cell vehicles. We will have a modest amount of battery assist on them in order to give them better acceleration characteristics, but essentially they are pure fuel cell vehicles. But for larger vehicles, having the hybrid technology with fuel cells is critical.

The key here is to get to electric drive. Electric drive has a lot of important advantages in terms of the driving characteristics of the vehicles. Fuel cells and hybrids have both of those.

Mr. SMITH. A quick question to you Mr. Garman, on the—John Graham and there seems to be inconsistency within the Administration for what the—how to progress on fuel cells.

Mr. GARMAN. Actually, I am not familiar with that specific——

Mr. SMITH. The EIA was complaining that their projection of hybrid vehicle market growth directly contradicts reports by auto makers in the United States. It seemed to be an in-house criticism and I was just wondering about the coordination.

Mr. GARMAN. The EIA is an independent statistical entity within the Department of Energy, and I can assure you there is no coordination between what they say and what we think. And we often have some—we often disagree with the EIA about the introduction of technologies, and it is a healthy disagreement.

I did want to add the point, however that we view the introduction of the interim technologies very importantly as well. We have sought—we are seeking this year more funding for hybrid vehicle technology work, as well as materials work—lightweight materials that we think will be importantly integrated in vehicles both in the midterm and the long-term as Dr. Burns indicated. And General Motors' vision of how the market is going to unfold and how consumers are going to become exposed to this new both hybrid and fuel cell technology and adapt to it is quite consistent with ours.

Mr. SMITH. Thank you, Mr. Chairman.

Chairman BOEHLERT. Thank you, Mr. Smith.

Mr. EHLERS [presiding]. Thank you, Mr. Smith. Next we will call on Mr. Miller.

Mr. MILLER. Thank you. I regret that I have been kind of in and out of this hearing and not been able to give it my full attention, so if I have—if I ask questions that you have already addressed, I apologize.

POTENTIAL BENCHMARKS FOR HYDROGEN VEHICLES AND FOSSIL FUEL ENGINES

I think I have questions that probably would be best directed to Dr. Burns, I think, but if anyone else has an answer, please speak up. You spoke of the need—well, the intermediate technologies before we have a full-blown hydrogen economy. Is there a magic number of miles per gallon that we would need to achieve for American vehicles that would allow us energy self-sufficiency? I have heard 37.

Dr. BURNS. I am not aware of such a magic number that we should be targeting. The fuel cell is twice as efficient as the internal combustion engine, and that is very encouraging. But you also have to recognize that as Mr. Huberts mentioned, you need energy to create the hydrogen, the form that it is stored—that exists in the nature with water with hydrocarbons. And so when you balance that all out, we think we could see about a 50 percent fuel economy or energy efficiency advantage with the fuel cells going forward. But we really don't have a magic number of that type that we would target.

Mr. MILLER. With—you are talking about with hydrogen. I am talking if you stick, for at least the time being, with the fossil fuel—with fossil fuel engines as the energy source for vehicles, what kind of fuel efficiency would you need to achieve to—for the United States to have energy self sufficiency?

Dr. BURNS. Again, I don't—sir, I don't see a magic number on that. The key is, though, the growth of the economy, and the growth of the economy is going to determine the energy consumption going forward. And if you look at vehicle miles traveled in this country, it has nearly doubled since 1980, so again, I don't see that kind of number existing.

Mr. MILLER. Dr. Ogden, do you have any better idea or——

Dr. OGDEN. I would second that. It really depends on the vehicle miles traveled. You could decrease, perhaps, oil use in the near-term by implementing more efficient internal combustion engine technologies, and as demand grows, you will probably reach a point where you need to increase the efficiency more. And looking at other sorts of externalities, people have estimated 100 years from now, even if you completely decarbonize the electric sector, if you want to get on a path we you are going to stabilize the atmosphere say at an acceptable CO_2 level, you are going to have to decarbonize the fuel sector very substantially, which will mean moving from hydrocarbon to something like hydrogen.

Mr. MILLER. Okay. I was thinking more immediate than over the course of the next 100 years.

Mr. GARMAN. Mr. Congressman, I will take a crack at that, because we did some very rough scenario analysis on that very question and found that even if we were to impose an immediate and, let us say, unreachable, but an immediate 60 percent increase in the CAFE standard to 38.4 miles per gallon and discovered a 10 billion barrel oil field on the north slope of Alaska and began pumping that at a rate of up to two million barrels a day, we would still not be energy independent. We would for a short time. And we did this based on extrapolating EIA data. We would, for a short time, begin to bend that jaw between domestic production and demand but only for a short time. After a while, that demand would once again expand. So I think that is a powerful argument that eventually we must turn to a hydrogen approach for transportation.

POSSIBILITY OF THE FAILURE OF A HYDROGEN ECONOMY AND POTENTIAL ALTERNATE PLANS

Mr. MILLER. A question then for you, Mr. Garman. We have continued to make remarkable technological advances, but they are not always the ones that we expected to make. And most of the folks who have called for a really serious effort in developing alternative fuels, a Manhattan Project for alternative fuels, has suggested we go off on several fronts at one time and see which one works. It does seem that this plan does put all the eggs in one basket, although the amount being put in this basket is not really that many eggs in view of how important alternative energy is to us. Is there a plan B? If this doesn't work out, what do we do? And when do we identify—are we setting out points along the way that we identify that this is just not working, we better turn our attention somewhere else?

Mr. GARMAN. Absolutely. As part of our FreedomCAR partnership, we have not only technology goals for 2010, but interim technology goals too, as well as off ramps on technologies once we determine that we are not succeeding in a particular technology, say onboard reformation of gasoline fuel aboard the vehicle. We have been putting money into this for some years, and if we are not achieving technological goals, we quit spending money on it. And we have off ramps. We subject our program to peer review by the National Academy of Sciences so that if we are on the wrong course, we know so that we can make adjustments in either the technology requirements or make the appropriate shifts.

Mr. EHLERS. The gentleman's time has expired. We recognize Congressman Rohrabacher.

Mr. ROHRABACHER. Thank you very much. And I apologize as well for being in and out today. I have other Committee assignments, as we all do, and this is just unfortunate, but I do consider this hearing to be of importance, and that is why I came back.

SOURCES OF FUNDING AND COST ESTIMATES

When I used to be a journalist, I used to ask one question. Everybody thought it was a great question and gave me a lot more credit than I deserved. And it was just one question I asked in so many different ways, and which is how much is it going to cost, and who is going to pay for it. And I think it comes down to a lot of what we are doing here. And I was wondering, first of all, is there or is there not an extra step that is required that requires energy which then costs money before hydrogen can be produced as a fuel? And am I incorrect in that? I mean my assumption is, okay, how much does that extra step cost? What is the percentage of that extra step to the end cost?

Mr. GARMAN. We have done well-to-wheels efficiency analysis, which we think is very important. You raise the critical point that if you are considering a new system, you have to take into account if you are using, for instance, a hydrogen fuel cell vehicle with compressed natural gas reformed into hydrogen. You have to count what is the energy penalty you pay of converting the natural gas to hydrogen? What is the energy penalty you pay taking the hydrogen and compressing it to put it aboard the vehicle? And we have done those analyses. The inherent greater efficiency of fuel cell vehicles more than makes up for the penalty in the conversion in these well-to-wheel analyses. I will provide for the Committee a complete well-to-wheel analysis. (See Appendix 1: Additional Material for the Record.)

Mr. ROHRABACHER. So in other words, a hydrogen fuel for a car, while it costs you to—it costs you more per gallon—I mean for a gallon, but you are getting many more miles per gallon?

Mr. GARMAN. Right. And let me also—so that I don't mislead you, our 2010 technology goal for hydrogen produced from natural gas is $1.50 per gallon of gas equivalent, untaxed. So it is more than that today. We think that advances in R&D will bring that down to the $1.50 per gallon of gas equivalent untaxed.

Mr. ROHRABACHER. All right. Let me make sure I am getting you straight. So that includes the cost of the natural gas and everything?

Mr. GARMAN. Yes. Yes, it does.

Mr. ROHRABACHER. Okay.

Mr. GARMAN. And that is based on $4 per MCF natural gas in that particular figure.

ABUNDANCE AND COST OF NATURAL GAS

Mr. ROHRABACHER. Okay. Now you are going to have to—other people may want to correct me if I am wrong, but I seem to remember that natural gas is not really as abundant as we thought it would be in the United States.

Mr. GARMAN. Prices are up, and but EIA estimates—the same EIA that we sometimes agree with and sometimes don't, so estimates that natural gas is going to continue in the roughly $4 per MCF range.

Mr. ROHRABACHER. And that is—unless we all convert over to automobiles, which then of course means natural gas will go way up in price.

Mr. GARMAN. And we have asked EIA to do that analysis for us, and they find that natural gas demand is not as much as you would expect in the early days.

Mr. ROHRABACHER. Well, of course not now, but if you have your way, the natural gas demand is going to be right through the roof.

Mr. GARMAN. Right.

Mr. ROHRABACHER. That means natural gas will go up to about, maybe, $10 a gallon, I would imagine.

Mr. GARMAN. Assuming we are successful, EIA has estimated, I think, between a three and five percent increase——

Mr. ROHRABACHER. Oh, come on now.

Mr. GARMAN [continuing]. In—that is EIA.

Mr. ROHRABACHER. Let me tell you, I mean, looking at the way gas prices fluctuate right now with minor disruptions or minor increases in demand, I—frankly, I—what you are saying doesn't make any sense to me at all. I mean, yeah, it does if you say that natural gas prices are going to stay the same and we are going to get it for $1.50, that makes all of the sense. But once you convert it to cars, that is bound to go up. My guess, it would quadruple——

Mr. GARMAN. Well, that is——

Mr. ROHRABACHER [continuing]. Because that is—because you are not talking about having to quadruple the use of natural gas, the margin is what counts in terms of price. What about——

Mr. GARMAN. If I could, though——

Mr. ROHRABACHER. Sure.

Mr. GARMAN [continuing]. That is—you are absolutely right, and that is why we do not want to depend on natural gas as our sole hydrogen source. The attraction of hydrogen is that——

Mr. ROHRABACHER. Right.

Mr. GARMAN [continuing]. You can produce it from multiple sources.

Mr. ROHRABACHER. Right. And——

Dr. OGDEN. Could I just chime in with one——

Mr. ROHRABACHER. Sure. Jump right in there.

Dr. OGDEN [continuing]. Quick thing on that, too?

Mr. ROHRABACHER. But I hope that the other sources we are talking about are acceptable to environmentalists. Like some environmentalists don't want us to have nuclear energy, for example. And yeah, that is a way to produce hydrogen, but you are not going to get any more nuclear power plants. Or maybe they don't like burning oil or coal in order to produce hydrogen because of the air pollution that that causes, so there seems to be some problems there. Yes, ma'am.

Dr. OGDEN. I have done some calculations looking at the question what if we converted all of our cars to hydrogen cars, we derive the hydrogen from natural gas, how much more natural gas will you need? And typically the numbers are like an increase of 25 to 30 percent in what we would be using anyway, which is not a negligible number, but it is not—you know, you won't increase the use of natural gas by ten times if you go to hydrogen——

Mr. ROHRABACHER. I mean, all of the cars that we are going around—if you convert all of them, it is only going to increase natural gas usage by 25 percent?

Dr. OGDEN. That is correct. And the reason for that rather surprising result is that——

Mr. ROHRABACHER. All right.

Dr. OGDEN [continuing]. Hydrogen vehicles are much more efficient—the projected hydrogen than current gasoline fleets.

Mr. ROHRABACHER. Well, we are on the record now, and there is going to be somebody who is going to—my guess within a week who is going to come up and refute that.

Dr. OGDEN. Well, also to my——

Mr. ROHRABACHER. But that is my—but that is just common sense speaking to me, and I have no—I don't have a Ph.D., so I can't——

Chairman BOEHLERT. Mr. Huberts, do you want to respond to that? Your time is up, but let us get Mr. Huberts' response.

Mr. HUBERTS. Mr. Congressman, I think that the point here is that by using hydrogen, the choice for primary energy becomes flexible. And that choice will depend on many factors, including environmental concerns, etcetera. If people want to have cars, they are going to need energy in one form or the other. Hydrogen then liberates those cars from being bound to petroleum. And that is the whole point.

Mr. ROHRABACHER. I have to tell you, that won't be the whole point for somebody if he ends up spending $3,000 a year more for fueling his car and he finds out that his kids now have a lower standard of living because we have freed him from petroleum. And I will have to see more before I will jump. I do know that we use hydrogen for our rockets. It is very effective. And it is a good fuel source, but you haven't convinced me——

Chairman BOEHLERT. The gentleman's time has expired.

Mr. ROHRABACHER. Thank you.

Chairman BOEHLERT. Mr. Bell.

Mr. BELL. Thank you, Mr. Chairman. Before leaving, Mr. Larson left a statement from one of his constituents, UTC Power, and it speaks to some of the issues being covered here today, and I would like to ask unanimous consent to have this entered into the record.

Chairman BOEHLERT. Without exception, and at the same time, I will enter into the record the statement by Mr. Akin and also a question.

WRITTEN STATEMENT OF UTC POWER (SUBMITTED BY MR. LARSON)

PREPARED STATEMENT OF UTC POWER

UTC Power, a unit of United Technologies Corporation (UTC), is pleased to submit the following comments regarding the House Science Committee's hearing entitled: "The Path to a Hydrogen Economy." UTC, based in Hartford, Conn., provides a broad range of high technology products and support services to the building systems and aerospace industries. UTC Power is focused on the growing market for distributed energy generation to provide clean, efficient and reliable power. One of UTC Power's businesses is UTC Fuel Cells, a world leader in the production of fuel cells for applications ranging from space to commercial to transportation.

We have attempted to be as specific as possible regarding our views on “The Path to a Hydrogen Economy” and have therefore used the “Energy Research, Development, Demonstration and Commercial Application Act of 2003” (H.R. 238) as the basis for our comments. Our recommendations include the need for continued “core” fuel cell research and development efforts, including proton exchange membrane (PEM) technology that can be applied to power plants for both stationary and vehicle products. In addition, we believe that stationary and fleet vehicle demonstration programs, including transit buses, are strategically important as building blocks for the longer-term successful deployment of fuel cell automobiles.

UTC Power supports the overall thrust of H.R. 238 and its recognition of the need for a focused research, development demonstration *and* commercialization effort to bring advanced, clean, energy efficient and cost effective technologies to the market place that will result in energy security, fuel diversity, improved air quality and other environmental benefits as well as technology leadership. While H.R. 238’s focus is on the research, development, demonstration and commercialization initiatives that fall within the scope of the Science Committee’s jurisdiction, we also note the need to address financial incentives, direct government purchases, removal of regulatory barriers, education and training and development of harmonized codes and technical standards.

The hydrogen provisions in Subtitle C of H.R. 238 are quite broad and call for a comprehensive program focused on production, storage, distribution and establishment of necessary technical standards. Success in all these areas is essential to ensure that the hydrogen economy becomes a reality. We are pleased with the growing awareness of the need to address hydrogen infrastructure requirements, but we should not lose sight of the continued need for basic fuel cell research and development efforts as well as strategic stationary and vehicle demonstration programs so that hydrogen can power the cars, trucks, buses, homes and buildings of tomorrow.

CORE FUEL CELL RESEARCH AND DEVELOPMENT PROGRAMS

Fuel cells face a number of technical challenges including reducing the system’s cost, size and weight while improving durability and performance characteristics. The industry also needs to address the efficiency and cost effectiveness of manufacturing processes and materials issues. While substantial progress has been made on many of these fronts, more work needs to be done. Continued investment in “core” fuel cell power plant technology is needed to reach these goals. We believe the government has a pivotal role to play in supporting high-risk core fuel cell technology R&D efforts on a cost-share basis with industry so the public at large can enjoy the efficiency, reliability and environmental benefits of fuel cell technology.

Title II of the Hydrogen Future Act Amendment of H.R. 238 addresses fuel cell demonstration programs, but does not include provisions that target basic fuel cell technology research and development. The Department of Energy’s Energy Efficiency and Renewable Energy organization should manage these ongoing technology programs as public-private partnerships. Programs that address low cost, high-efficiency, fuel flexible, modular fuel cell power systems, improved manufacturing production and processes, high temperature membranes, cost effective fuel processing for natural gas, fuel cell stack and system reliability and durability and freeze/cold start capability all should be part of the ongoing core fuel cell component and systems research and development effort with a focus on PEM technology initiatives. These core PEM research and development efforts can be leveraged across stationary and transportation fuel cell applications for maximum return on investment to U.S. taxpayers.

FUEL CELL BUS DEMONSTRATION PROGRAM

Fleet vehicles and transit buses in particular are ideal candidates for the initial deployment of fuel cell vehicles. Hydrogen storage is less of a problem because of space availability on the roof of buses and the bus installation is more forgiving compared to personal automobiles in terms of cost, size, weight and performance characteristics. And hydrogen fueling stations and technician training can more readily be made available given the relatively small number of inner city bus stations and service technicians.

Since the automotive application is the most demanding in terms of cost, weight, size, durability, ease of maintenance, start up time and other performance criteria, it is understandable that it will take longer for fuel cells to successfully compete in this market. But as the industry gains experience in deploying fuel cells for stationary, inner city buses and fleet applications, these successes can pave the way for zero emission fuel cell cars and serve as benchmarks to measure progress towards the 2010 goals of the FreedomCAR initiative.

H.R. 238's Sec. 402 of Subtitle H establishes a $200 million program for the acquisition of alternative fuel and fuel cell vehicles through DOE's Clean Cities program. We believe a zero emission fuel cell transit bus demonstration program is needed as a precursor to the fuel cell vehicle acquisition program. Specifically, we recommend that a new provision be added to H.R. 238 that establishes a national, zero emission, petroleum-free, hydrogen fuel cell bus demonstration program.

This public-private partnership would focus on the design and production of fuel cell power plants, bus chassis, electric drive and other components, hydrogen infrastructure requirements, data collection, testing, evaluation, information dissemination and training of operators and maintenance personnel related to the demonstration effort. The program should deploy a minimum of 10 buses in geographically dispersed cities located in air quality non-attainment zones as part of a five- to six-year program.

UTC Power believes that demonstration efforts for heavy-duty vehicles should begin with transit buses rather than school buses. Sec. 302 of H.R. 238 calls for a $25 million fuel cell school bus program from FY 2004–2006. We believe this program should follow the zero emission fuel cell transit bus demonstration program. The fuel cell school bus program can therefore build on and take advantage of the lessons learned from the transit bus demonstration program.

FUEL CELL VEHICLE DEFINITION

Section 401 of H.R. 238 defines a fuel cell vehicle as a "vehicle propelled by one or more cells that convert chemical energy directly into electricity by combining oxygen with hydrogen fuel which is stored on board the vehicle in any form and may or may not require reformation prior to use." This definition appears to exclude hybrid fuel cell configurations. Our proposed definition would be a: "vehicle propelled by an electric motor powered by a fuel cell system that converts chemical energy into electricity by combining oxygen (from air) with hydrogen fuel that is stored on the vehicle or is produced on-board by reformation of a hydrocarbon fuel. Such fuel cell system may or may not include the use of auxiliary batteries to enhance vehicle performance."

DISTRIBUTED ENERGY-COMBINED HEAT AND POWER (CHP)

UTC Power would also like to take this opportunity to comment on the need to expand Subtitle B to permit the demonstration of energy efficiency enhancing products and technologies that may be used in combined heat and power and waste heat recovery applications. These approaches use "free energy," if not renewable energy, and draw upon core technology already in existence. This means these technologies can reach the market rather quickly and their benefits can be realized in the near-term. We recommend that Subtitle B, H.R. 238 be amended to broaden the scope of distributed generation demonstration initiatives beyond hybrid systems and specifically include distributed generation demonstration programs to validate products and technologies that may be used in combined heat and power, building heating and cooling power and waste heat recovery applications including waste-water treatment facilities, landfills, industrial process heat and central heating/boiler systems.

In conclusion, UTC believes that a sustained, robust commitment to the hydrogen economy is necessary to make this vision a reality. Progress has been made, but continued commitment and support of core fuel cell research and technology is essential, with additional emphasis on strategically focused fleet vehicle, including transit bus, demonstration programs.

We appreciate the opportunity to comment on this important initiative. Should you have any questions regarding this matter, please contact Judith Bayer, UTC's Director, Environmental Government Affairs at 202–336–7436 or Judith.bayer@utc.com.

BEST USE OF SCARCE RESOURCES (SUBMITTED BY MR. AKIN)

REMARKS AND QUESTION FOR DAVID GARMAN—MR. AKIN

Mr. Chairman, as we have seen, the road to greater use of hydrogen in our economy faces many challenges which demand considerable time and effort. I would like to commend the witnesses today for their commitment to the President's Hydrogen Initiative and their work thus far. In the past, we have tried to address our energy dependency through the research and development of vehicle technology without the necessary infrastructure, with little regard to the importance of consumer demand and with a disturbing lack of concern for practical implementation of protracted research. I commend the witnesses in their efforts to provide us with a plan that addresses both long- and short-term concerns relating to a hydrogen economy.

My question is: I have noticed in the FY 2004 budget request that DOE is requesting $17.3 million in renewables for hydrogen production. However, in the Department of Energy's Hydrogen Energy Roadmap, you note that such methods as solar heat and photoeletrochemical electrolysis are still in early development stages. Do you feel that an investment of $17M is the best use of scarce resources or do you feel that part of this money could be more appropriately used in other areas of hydrogen production such as natural gas?

Chairman BOEHLERT. And all of the witnesses should know that there will be some follow-up written questions for you. We would appreciate a timely response. Mr. Bell.

Mr. BELL. Thank you. With that, in the spirit of shameless Congressional district self promotion, I want to point out that the Houston Advanced Research Center, known as HARC, recently announced the successful connection of a five-kilowatt proton exchange membrane fuel cell system into the electric grid. The technology, which is patented as the Plug Power System, is the first in the HARC study to be located outdoors in real world conditions and the first residential unit to be connected to the electric power grid in Texas. And the purpose of this recent demonstration is to test the feasibility of putting energy into HARC's internal grid to learn whether homes in the future can safely generate their own power and receive emission reduction credits from on-site fuel cell installations. This is just one example of how HARC's partnership is taking the lead in shaping Houston as a promising site for fuel cell technologies.

HARC's work demonstrates how Houston, the Nation's energy capital, and I want to note that Mr. Lampson tried to expand the Nation's energy capital to all of southeast Texas, but it is really Houston. He is trying to get a little bit of it in his district as well. He will have a chance to refute it, I am sure. But we really are trying to take the lead in exploring alternate energy sources.

TIMETABLE FOR CONVERSION TO ALTERNATE ENERGY SOURCES

There has been a lot of talk and some here today about the timetable and how long this might take to make the conversation to alternate energy sources. Some have predicted that it could take decades. And I am curious, given the energy supply situation, the energy cost situation in the United States, can we afford for it take that long? And Mr. Garman, I will start with you on that.

Mr. GARMAN. Some individual consumers are determining that they want hydrogen fuel cells now. And they may be in a particular situation that—where they have a reliability requirement, such as an Internet data hotel, if you will, or something that absolutely needs reliable power, high-quality power, and they are willing to make that investment at current prices. I believe Verizon—the Verizon communications company is installing fuel cells in many locations in its critical infrastructure, and they are willing to pay the additional price. So I think you are going to see these technologies coming into the marketplace both as a consequence in the R&D work that is bringing the cost of the technology down, but also because of the individual needs of particular consumers that have a specific requirement for niche applications are willing to pay a little extra now for that. So you will see both of those things happening.

Mr. BELL. Mr. Huberts, do you care to——

Mr. HUBERTS. I guess, first of all, we are aware of HARC initiative and Shell has decided last month to join that initiative. I think that the stationary power certainly is an application that can take place in a nearer term than transportation. And I think the sort of initiatives that are going on will expand, and we will see in the next three to five years more and more of those stationary fuel cells coming on the market, and they are going to be real commercial applications.

NECESSITY OF COMPETITION TO SPEED DEVELOPMENT

Mr. BELL. Let me ask this, because my time is short, but Mr. Garman, you talked—spoke earlier about as more competition develops in this area that will speed development. And I want to commend Shell, because you all have also funded the Center for Research at Rice on sustainability and truly seem to be a company that gets it and knows that there needs to be this concentration on the future. But if there isn't greater participation or is there enough participation right now in this area to spur the kind of competition that you are talking about? Would either of you like to comment on that?

Mr. GARMAN. I think the President's expression of a national commitment in this area is something with his resolve saying we, as a nation, are going to do this. I think that, first of all, sends a signal to the market. 720 million new dollars, 1.2 billion sends a signal to the market. But more important than that, really, I think the partnership that you see really on this table in front of you, these are some of the same folks that have worked with us over the past year or more on developing the technology road maps that we need. And they are the ones that are putting their own money up and investing their own money in these technologies and betting that they are going to be successful. I think that is an illustration of resolve, not only at the national level, but also the private sector putting its money where its mouth is.

Mr. BELL. Would you like to comment on that?

Mr. HUBERTS. I would say that—you mentioned you received fuel cells. We have been partnering with them. We are developing the processes required to make the hydrogen for their fuel cells. It requires investment, but we see tremendous commercial opportunity there, and we see that in a time frame with the stationary fuel cells that is much closer than with transportation. So it is an area where it makes sense to invest. It makes sense for business to participate.

Chairman BOEHLERT. The gentleman's time has expired. Dr. Ehlers.

Mr. EHLERS. Thank you, Mr. Chairman. Since I appear to be the last person to ask questions, at least in the first round, let me just summarize what I believe I have heard and learned and see if any of you disagree with that, and then I will have a few questions after that.

Number one, fuel cell technology is well underway. That is the least of our problems at this point. The main effort there is cost reduction and efficiency improvement. Secondly, hydrogen, if it is going to be a viable fuel, must be produced efficiently and used efficiently. Thirdly, the President made a point in his speech of mentioning carbon sequestration, so I assume the objective is to either produce the fuel from non-carbon sources or sequester the carbon that is used in producing the hydrogen.

Next, we must find the best way of producing hydrogen. And that—it seems to me, there is a considerable uncertainty about that. What is the best scientifically, economically, and environmentally? Next, we have to also find the best way of transporting hydrogen and distributing it. And that, I think, may be the biggest problem that we are going to face as a Nation with distributive responsibilities between the government and the industry. Next, because the timeline is longer than any of us would like, that we will have to, in terms of our goal of reducing dependence on foreign oil, we will have to have a transition technology of probably hybrids to bridge us to the hydrogen economy.

Development of Codes and Standards

I am hoping that this is a reasonable summary of what you have said and what I understand. And I would appreciate any comments on that. Before I get to comments, let me just say Mr. Huberts mentioned codes and standards. I think Mr. Lampson also addressed that. A specific question for you, Mr. Garman, are you involved in developing those codes and standards and will you be working with NIST, the National Institute in Standards and Technology, on this since they have two centuries of experience in developing those?

Mr. Garman. Yes, Congressman. We envision an interagency group that is under the leadership of the Office of Science and Technology Policy and the Executive Office of the White House convening interagency activities, which frankly are already underway involving not only NIST but at the Department of Transportation and other federal agencies involved in the codes and standards issue. In fact, Secretary Abraham is leaving tomorrow for a trip to Europe to discuss harmonization of long-term codes and standards with his counterparts in EEU, stressing the importance of that particular activity. And we have, in our budget line, tripled our own work for safety code standards and utilization for hydrogen.

Additional Cost of Carbon Sequestration

Mr. Ehlers. Okay. The next specific question, if sequestration is going to be required, and I assume it is, that means any methods of producing hydrogen are going to have to assume the cost of sequestration. And it also means that we are not likely to use the technology that is being broached right now of using petroleum or natural gas fuels on cars and reforming it on board the car, because you can not sequester the carbon at that point, I believe. Is that correct?

Mr. Garman. Over the long-term, you want a net zero carbon emissions profile. Now I would modify that by just pointing out that even if you are using natural gas in the near-term, because it—the carbon intensity, if you will, of natural gas is much lower than other hydrocarbons, you would get a 60 percent reduction in carbon emissions from vehicles using hydrogen reformed from natural gas without sequestration than you would from vehicles using gasoline just because of both the lower carbon density in the natural gas and the higher efficiency of the natural gas vehicle.

Mr. EHLERS. But my concern is that proposals within the automobile industry to use gasoline or perhaps natural gas, but initially gasoline in reforming it, will impede the development of the infrastructure you need for a full hydrogen economy. If you start producing cars that way, people will say, “Oh, good, I can still use the gas station.” And that removes the emphasis for developing the hydrogen transportation production and infrastructure. Is that——

Mr. GARMAN. That is fair. I have heard that criticism. Yes, sir.

Mr. EHLERS. Okay.

Chairman BOEHLERT. Dr. Ehlers, you will have a second round, but your time is up in this round.

Mr. EHLERS. Yeah. I just wonder if there are any quick reactions to my summary, since I have to leave, I have a vote going on.

Dr. OGDEN. Could I give one real quick reaction?

Chairman BOEHLERT. Sure, Dr. Ogden.

Dr. OGDEN. One is the—I think it was really a good summary, but one thing I would sort of add is that there may be no one best way to produce hydrogen. It is sort of like producing electricity. There are lots of different ways you can produce it, and lots of carbon—net carbon neutral ways of producing it as well, not only fossil fuels or sequestration but renewable energy as well. And so there really is a large diverse portfolio of long-term options that could get you there.

Mr. EHLERS. That is certainly true. But I think you do have to zero in on a method of distribution and using it and putting it into the vehicles.

Dr. OGDEN. Yeah, I certainly agree on that.

Mr. EHLERS. Because if you have competing options there, it adds to the expense.

Dr. OGDEN. Agreed. Yes.

Mr. EHLERS. But I agree that production can be any method whatsoever. Thank you.

Chairman BOEHLERT. Thank you very much. Mr. Lampson.

ABILITY TO BE HYDROGEN RELIANT BY 2040

Mr. LAMPSON. Mr. Garman, in your testimony, you describe a four-part approach to moving toward a hydrogen economy with a full shift some time around 2040 or so. That is a wonderful goal. Is it pretty much correct, do you believe, that you can be—have us pretty much reliant on hydrogen, completely reliable on hydrogen by 2040?

Mr. GARMAN. If we are successful in meeting our R&D goals in the short-term and industry does, on the vehicle question, make its commercialization decision around that 2015 time frame, then the answer is yes. Obviously, we have some daunting technology goals, as we have discussed this morning, and if we miss a few, the date can slip. And this is scenario analysis, similar to what Shell does trying to envision the future. It is impossible to predict the future, so we do the best that we can envisioning different ways the future might unfold.

Mr. LAMPSON. Thanks. Let me ask all of the rest of the panelists now, if you will comment on this. Do you believe that the President's Hydrogen Initiative, as Mr. Garman has laid it out, will result in a complete transition to a hydrogen economy by 2040 or so, and if not, why not? What does the plan lack? And what are realistic goals?

Dr. BURNS. My—I will go ahead and go first. Yeah. I certainly think it is a very important first step, because it has put this issue on the national agenda and it provides an opportunity for everybody to pull together with a common will to make it happen. But it certainly is not going to be sufficient with the level of funding that we are talking about. General Motors, for example, has already spent nearly $1 billion to develop our technology to the point that we have it today. And if we are successful in meeting the goals we have set for ourselves in the next five years, we will likely spend more than the President's program, as our company ourselves, in order to move it forward. I think it is a very important first step, because of the national agenda aspects of it, and it allows us to all talk about it. But there is an awful lot of work to be done, an awful lot of uncertainties that need to be addressed, and we don't know what we don't know at this point in time. So we are going to have to take some important first steps and learn as we go forward.

Chairman BOEHLERT. A journey of a thousand miles. Continue.

Dr. LLOYD. Oh, I totally agree with Dr. Burns. And I think the other question is I don't think we can afford not to look at that scenario and push as rapidly as is possible for the reason I mentioned, security of many sources. And again, I will—I think that with the type of partnership we are working with at the local level, state level, national level, I think it is critical, because the other part of it, there are international competitions going on. And I think it is very, very important.

I would like to come back to one issue just to set the record straight when I talked about the competition, particularly with a Japanese company. I did want to highlight, I think, the very successful event that General Motors had out in Sacramento, which I think demonstrated the GM technology—the very best a while ago and attribute to Dr. Burns and Dr. McCormick where they run all through their hybrids then right through the fuel cell, also to the high wire. And I think as we discovered during the partnership when Dr. Huberts was Chair, that in fact, what you see there, the public has a vision of what can be done with the hydrogen and the fuel cell, coupling that together. And I think General Motors is—has demonstrated that better than anyone. And I think that is the part we also need to focus on. Give the public something that becomes irresistible. We hadn't talked about today the opportunities to use the vehicle as a source for energy into the house. All sorts of possibilities open up, and I think Dr. Burns and Dr. McCormick are on the very forefront of looking at how we can couple this together. The bottom line is we can not afford not to do this.

Mr. LAMPSON. Thank you. Dr. Ogden. Oh, do you want to—okay. Okay. Thanks. Go ahead.

Mr. HUBERTS. I think the President's Initiative is very important. I think what is also very important is that the policies are sustained and consistent. And as Mr. Garman pointed out, it is a long-haul effort. This is a marathon. We don't want to run out of steam after the first mile, so if you start too big too soon, sinking too much money into something that is still too expensive that is not sufficiently developed, you are going to run out of steam. So it needs to be a measured effort. Is it modest? Yes, it is modest. Could it be bigger? If you can afford it, make it bigger, but don't start too big, because this is something that needs a long-haul commitment.

Mr. LAMPSON. And Dr. Ogden.

Dr. OGDEN. I think going back to your question about is the sort of time frame that was set forth of 2040 a reasonable thing, I think if the technology advances and if they are successful, then it certainly is a sort of a reasonable thing. Is it an absolute certainty that will happen? No, there are lots of unknowns we don't know about how fast technology will progress, how we will value the things that hydrogen fuel cells could give us in a society in terms of energy, security, and environment. And it could go faster or slower than that, but I think that what was presented there is a reasonable look at what would happen, assuming the technological success and a decision to commercialize.

Chairman BOEHLERT. The gentleman's——

Mr. LAMPSON. Thank you all very much.

Chairman BOEHLERT. Thank you.

Mr. LAMPSON. Thank you, Mr. Chairman.

EFFECT OF POLICY ON THE RESEARCH AGENDA

Chairman BOEHLERT. Mr. Garman, you touched on this a little bit in your exchange with Dr. Ehlers, but you indicated in your earlier statement that it is a little bit early to worry about policy, but aren't there policy decisions that will effect the research agenda? For example, won't environmental rules effect the choice of hydrogen sources? And won't sequestration change the way that projects are designed?

Mr. GARMAN. Absolutely. And I think—and perhaps I misspoke, because I was thinking about a narrow range of policy incentives for the purchase of these technologies rather than the broader context of policy measures that perhaps you are—I think, as I indicated in the testimony, the announcement last week in the administration of the future generation approach to integrated coal fired power plants that emit nothing, including carbon and sequestration are an important technology development that we have to consider very strongly. And absolutely, sequestration—the dollars in the President's Hydrogen Initiative, I want to make sure that everyone understands, do not include dollars for sequestration. That is an associated technology, but that is apart from the dollars we are asking for for hydrogen.

ADVICE FROM THE PANEL AS TO WHAT THE GOVERNMENT NEEDS TO DO TO FURTHER A HYDROGEN ECONOMY

Chairman BOEHLERT. Give us—all of the—give us the best advice you can. What can we do, obviously approve the funding that is requested by the President, but short-term, what do we need to do? What would be your best advice for us? And let us go across the board. Mr. Huberts, do you have anything?

Mr. HUBERTS. I would say, in the short-term, as a government, be also a user of this technology. Set an example of trying to use this in fleets, in buildings, in defense applications——

Chairman BOEHLERT. So high profiled demonstration projects that have some real meaning?

Mr. HUBERTS. Try—yes, try to get learning and education and also benefits, real benefits. And I think that is something that can be done in the short-term, and it would help the industry in buying down the costs.

Chairman BOEHLERT. Mr. Garman, any special high profile demonstration projects thought about at this stage of the proceeding?

Mr. GARMAN. We are—we have sought, I believe on the order of $13 million, Steve will correct me if I am wrong, for work in demonstration efforts in the early—for the '04 budget. An important word about demonstrations, though, I think it is important to stress that—and I think it is fair to say that the Department of Energy has something of a checkered history and record with respect to demonstrations. Sometimes the Department has done some demonstrations that weren't all that sensible. And sometimes, Congress has asked us to do demonstrations that weren't all that sensible. And I think it is very important that we come together and make sure that the limited amount of money that we do have for demonstrations is really spent to learn what we need to learn to provide the proper kind of feedback to the folks in the lab doing the R&D work rather than just, you know, showcasing the technology. They have to be—we have to get something out of these demonstrations. And that is something we all need to be mindful of.

Chairman BOEHLERT. Dr. Burns, do you have any thoughts that you would like to share with us?

Dr. BURNS. Yes, I would like to reinforce the learning aspects, and also to tie the demonstrations to real customers, early adopters in particular. The military is showing a high degree of interest in technologies that allow them to reduce the logistics requirements for fighting battles. And hydrogen and fuel cells are unique in that they address two of the three largest requirements for logistics fuel and water, and they are interchangeable. And that flexibility is quite important. Having opportunities to do demonstrations on military bases where we have highly trained military professionals who will be working with us in the development of those codes and standards. And they also will become civilians at some point who can become our engineers and technicians and customers for these technologies would be very beneficial.

I also just want to emphasize that stationary applications or distributed generation is where the first profitable markets likely will exist. So initiatives in the short-term that can encourage those opportunities would be much appreciated.

Chairman BOEHLERT. Thank you very much. Dr. Ogden, do you have a——

Dr. OGDEN. I would say that this is a really great opportunity to take a really long-term view of energy policy and that that has now started with looking as hydrogen as a long-term option in the fuel sector. So just opening that dialogue of ways to do this, I think demonstration projects are very important for people to see how this really works, for there to be open learning about this, what works, what doesn't work, as we go down this road toward looking at something that could be a very valuable technology for our country in the long-term.

Chairman BOEHLERT. Thank you very much. Dr. Lloyd, do you have any observations?

Dr. LLOYD. Yes. I would say continuing—continuity of funding, I think, was identified before from the government. I think that is important. It is not a one-way street, though. I also think we need continuity of support of working with the industry so that these are actually sustained commitments, so it is a true partnership. I think the California Fuel Cell Partnership is a great example of how we are all working together. Clearly, we recognize that is limited. We would hope that DOE would look at other national partnerships, realizing these can't be duplicated everywhere, but maybe strategic locations throughout the country.

So I think that, again, we have a model here, and I think that my advice would be to follow along the lines we have discussed earlier. And I think that providing adequate funding, providing adequate oversight, and also providing, again, the stimulus not only when we talk about some of—the buy down program, which I think is very important. And I think that was highlighted, the Federal Government has and can continue to play an important role there. But I think the other part of it, when we look at some of the cost sharing that DOE has, what I would suggest there is take a look at some of the areas where maybe some small, innovative companies with high-risk ideas, they may not have the resources to do some cost sharing. So as I indicated in my testimony, take a look at that, maybe reducing cost sharing as the Secretary has the discretion to do that. And maybe also look at some small business aspects, because we have been working on hydrogen storage and generating for many years. DOE has been working on that. We still have not come across the silver bullet. We need all the best ideas we can get.

Chairman BOEHLERT. Thank you. Taking notes, Mr. Garman?

Mr. GARMAN. I just—if I could just quickly correct the record. I said that there were $13 million in the '04 budget for demonstration work, that is only on the infrastructure side. We have $15 million on the vehicle side, so the total is——

Chairman BOEHLERT. About 28.

Mr. GARMAN.—28 million. Yes, sir.

DETAILS OF THE DECISION-MAKING PROCESS AT THE CALIFORNIA FUEL CELL PARTNERSHIP

Chairman BOEHLERT. That is good, because 13 million is petty cash around here. Thank you very much. Mr. Bell, have you got your question in? Do you have any questions? Let me—Dr. Lloyd and Mr. Huberts, as the current past chairman of the California Fuel Cell Partnership, would you comment on the process the partnership employs in making decisions on what projects deserve support? And specifically, what kinds of demonstration projects are most needed right now to promote the adoption of hydrogen technology? Dr. Lloyd, do you want to go first? Or Mr. Huberts? Do you want to flip a coin?

Mr. HUBERTS. I will go first. The process we use in the California Fuel Cell Partnership is a decision making process based on consensus. So we have 20 partners around the table who together decide what kind of studies we do, what kind of project we support and how we support those. There is a consensus making process. We deliberately chose that process, because we have so many different interests around the table that if we did it any other way, we would lose, sooner or later, certain of the members.

On what projects are important, certainly in the infrastructure area, we need to test out different options for producing hydrogen and also what we need to do in California is integrate those into the corner gas station. As you know, Shell is going to do that here in Washington. It is something that we believe needs to be done also in California, integrating it into the real life situation. How does the design work? How do you get through the process? How do you make it customer friendly? All of those aspects we need to test out in practice. And the partnership is very well suited for that, because it provides a framework for having a volume of vehicles there and also it provides the framework for learning. We have different energy companies working together there in a pretty competitive R&D situation. We can share information about safety issues for everything, etcetera. So that is where we will be focusing in the years ahead.

Chairman BOEHLERT. Thank you. Dr. Lloyd, do you care to add anything?

Dr. LLOYD. Yes, I would. Again, I think it has been a wonderful example of, as Don said, consensus building, which to me has benefited tremendously. I think we have got partnership stations. We have got partnership infrastructure. We have got partnership activities as we have exposed those to public. We have got our own—I have mentioned, we have got our own partnership stations in the north of California and growing in the south.

But we also have partnerships growing up, so that, as Don mentioned today, you see one coming out in Washington. But we also have partners working in California, so—as we have seen with Toyota and with Honda getting vehicles and DiamlerChrysler, Ford, etcetera, working with some of the various partners and government partners. So in fact, I think that that is being greatly facilitated by the partnership having all of the appropriate partners together at the local level. And we have seen the great benefits of having DOE—DOT, who does a lot of work on the safety side, and EPA, in terms of certification of some of these fuel cell vehicles. So I think that—again we hope that this could be a model for a lot of things that could be going on.

The other—I will just make one other point, if I may. One of our partners, for example, the South Coast Air Quality Management District has been very aggressive in natural gas vehicles. They are now also encouraging and may be requiring that the compressors used for natural gas be compatible with hydrogen. That is a cost savings that in the future when hydrogen is there, you can make that compatible. There are also discussions of using hydrogen engines to get—in fact, get the infrastructure out there. So all of those things are going on. And that was not part of the fuel cell partnership in that case, but through the partners.

Chairman BOEHLERT. Thank you. And I think the President and the Administration deserve a great deal of credit for elevating significantly the profile of this issue. The State of the Union, you can't get a higher profile than that. And this is but the first of many hearings we are going to have on this subject, not just in this committee, but in the various Committees of the House and the Senate. And we are excited about the prospects for the future. And we are excited about the partnership that is obvious within the private sector. We are excited about what DOE and your people are doing. And you are going to be hearing a lot more from us about this.

And with that, for the last word, I turn to the Distinguished Chair of the Subcommittee, Ms. Biggert.

RE-ALLOCATION OF FUNDS AT DOE IN ORDER TO ACCOUNT FOR THE HYDROGEN INITIATIVE

Ms. BIGGERT. Thank you very much, Mr. Chairman, for those kind words. I just have a quick follow-up question and maybe one more. And that is Mr. Garman again, and I—you said that the Hydrogen Initiative involves 721 million in new funding. And the remainder of the 1.2 billion is reallocated funding. So I am still not sure where this goes. So can you be more specific about where the new funding is going and what programs will be subject to reallocation, like, for instance, if your office is going to get the new funding while the Office of Science will have to reallocate its existing resources to contribute to the Hydrogen Initiative?

Mr. GARMAN. No, the difference is between—in the new funding is between the base that we were already funding and the additional dollars that will be added on top of that base, so to put it in another way, nobody's ox will get gored to fund the initiative.

Ms. BIGGERT. All right. So there won't have to be any cuts, like in looking at solar power or any of the new other initiatives? Those are still going to be important to this?

Mr. GARMAN. The planning profile that we have been provided can accommodate a robust renewable energy program as well as this new initiative as well as the President's commitment on weatherization funding and some of the other work that we do in our office.

Ms. BIGGERT. Okay. So it will focus on alternatives as well as the hydrogen?

Mr. GARMAN. Yes, ma'am.

TIMETABLE FOR STATIONARY VS. VEHICLE FUEL CELL USAGE

Ms. BIGGERT. Okay. Then just to follow-up, at a field hearing that we held last June, it was apparent that people—I don't think that very many people realize that fuel cells have applications other than automobiles. And that—and one statement was made there that we are likely to see a fuel cell installed in a home or a subdivision or—long before we are going to see that under the hood of a car. And that—so is this program going to focus on the use of hydrogen for stationary fuel cells as well as, you know, to power homes, office buildings, as well as the FreedomCAR? I mean, does the FreedomCAR include that within the program?

Mr. GARMAN. Yes. And you have raised a very important distinction. We think that the first fuel cell applications you will see are in consumer electronics. And then you will see it then in stationary applications, and then you will see it in vehicles. It is—we are working on vehicles, because they are the hardest in terms of weight, cost, you know, to get a fuel cell down to, you know, 35 cents a kilowatt. That fuel cell—that proton exchange membrane, polymer electrolyte membrane fuel cell will be economic long before that when it is in the hundreds of dollars per kilowatt in a stationary setting. So what we are really doing is we are going after the hardest thing we know to go after. And the ancillary benefits for stationary and these other applications will accrue as well. And the work that we are doing in hydrogen storage and production will benefit those stationary and earlier applications as well. Yes.

Ms. BIGGERT. Thank you. Would anybody else like to comment on that?

Mr. HUBERTS. I just—Mr. Garman, you said 35 cents per kilowatt. Did you mean $35?

Mr. GARMAN. No, I am sorry. I meant $35 per kilowatt.

Ms. BIGGERT. I was impressed.

Dr. BURNS. We see some very exciting business opportunities associated with distributive generation. David used the number of $35 for the stack. We think in terms of what we call the power module, which is also the storage of the hydrogen as well. In the area of $500 per kilowatt to $1,000 per kilowatt, there is a wide range of business opportunities in distributive generation. We call that premium power. These are customers who absolutely can't have their power go down, because it is very costly. Some financial companies would experience losses as much as $5 million an hour if they lost their power and couldn't do their transactions. So those business incentives are very significant to have the opportunity to apply the technology in a more stationary environment, which is less aggressive than in the automobile environment, allows us to learn from a durability standpoint, allows us to learn from handling of the hydrogen and the safety systems and other things, quite honestly allows us to generate some revenue and hopefully some profit that will help continue to feed the kinds of investments we will need to make to get to $50 per kilowatt for a widespread automotive application. We believe that is possible, and we think it is a great way to roll out the technology.

Ms. BIGGERT. Thank you. I, too, thank you for excellent presentations and look forward to continuing the discussion on hydrogen. Thank you.

Chairman BOEHLERT. Thank you very much. Mr. Garman, I can't close without revisiting the ox being gored. I mean, I think—can we agree that it is subject to interpretation and further discussion, I mean, investment and industry efficiency program is down. We are great in this committee. We want all of these areas to go up, because they offer such great, great dividends for mankind, our investment in these programs. And so would you agree that it is subject to further discussion?

Mr. GARMAN. Absolutely, Mr. Chairman. It——

Chairman BOEHLERT. With that—the State Department could use you. You are a diplomat. I want to thank all of the witnesses for being such informative resources for this committee. And while we will end the panel and the deliberation today, we will not end the relationship that we have established with each of you, and you will be receiving additional questions in writing. And on occasion, you can expect to receive calls from some of our brilliant staff people back here, because we are partners in this venture. And it is exciting. And I think we—what we are about offers great promises for the future. I think we are all guilty of a major sin if we overstate the case, but we can be enthusiastic as we look forward, and if we maintain this great partnership, evidenced by the venture you announced today, GM and Shell, and the open relationship you have with our government. And you know—and when Dave Garman says, "I am from the government. I am here to help," don't laugh. Say, "We want to work with you to help." And together, I think we can move forward and accomplish something worthy of note. Thank you so much. This hearing is adjourned.

[Whereupon, at 2:42 p.m., the Committee was adjourned.]

Appendix 1:

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by David K. Garman, Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy

Questions submitted by the House Committee on Science

Q1. Toward the end of the hearing, you indicated that you agreed that policy choices can affect the research agenda for the Hydrogen Initiative.

Q1a. Which policy decisions need to be factored in now as you shape the research agenda?

A1a. In order to ensure that the Administration's hydrogen efforts are well coordinated and consistent, the Department considers a variety of relevant Administration policies in deciding its R&D agenda. Foremost among these is the President's National Energy Policy, which provides both guidance and context for our hydrogen R&D efforts. As policies change, the Department will revisit its research agenda to ensure that such changes are incorporated.

Q1b. How, for example, will you decide which sources of hydrogen to focus on?

A1b. Energy security is best achieved by generating hydrogen from diverse domestic resources, such as renewables, nuclear and fossil-based resources. Only through this diversity can vulnerabilities from disruptions in supply be reduced.

Q1c. How will you decide how much emphasis to give to carbon sequestration?

A1c. Carbon sequestration is one technology in a robust portfolio of R&D activities. It is a key technology if fossil-based hydrogen production is eventually to be free of greenhouse gas emissions. As with other programs, funding allocations for carbon sequestration will be based on relative priority, program performance, expected potential for public benefits, alignment with the Administration's R&D investment criteria, and other factors.

Q1d. Can such research decisions be made without making assumptions or decision about the future policy environment?

A1d. The Department's R&D efforts are designed to facilitate a fuel cell vehicle and hydrogen infrastructure commercialization decision by industry by the year 2015. It is quite clear that the policy environment, and market conditions, existing at that time will influence those decisions by industry. However, the future 2015 policy environment is highly uncertain and not something that can usefully guide the Department's research agenda—which is targeted at addressing known high risk technology barriers. As our research efforts continue to produce key results and as both the near- and longer-term policy framework develops, we will reassess whether changes in the research agenda are needed.

Q1e. Does the Department believe that auto manufacturers would begin offering fuel cell cars in 2020 absent government involvement—whether that be tax incentives, infrastructure investments or regulation?

A1e. Given current policy conditions and technology challenges, the Department believes that it is unlikely that auto manufacturers would begin to offer fuel cell vehicles in 2020 absent government involvement. However, it is premature to speculate what kind of specific policy instruments will be appropriate at that time.

Q2. In response to a budget question from Mrs. Biggert, you stated that, "nobody's ox is going to be gored" by funding increases for the Hydrogen initiative, and that future funding profiles will provide for "a robust renewable energy program." Yet the FY04 request proposes to cut the energy R&D programs within EERE that are not related to hydrogen by eight percent compared to the FY03 request. In fact, some programs, such as the biomass and industrial technologies programs are reduced by almost 30 percent. How do you reconcile this fact with your statements that other programs are not being sacrificed to pay for the hydrogen initiative? Does the Administration assume that the outyear funding for the hydrogen initiative will also come primarily from cutting other EERE programs? Will the Office of Science programs be cut to pay for the hydrogen initiative as well?

A2. EERE funding from FY 2003 to FY 2004 is relatively flat. EERE's FY 2004 request for every non-hydrogen R&D program except Biomass and Industrial Technologies remains nearly level with its FY 2003 request level or Congressional appropriation. Funding for Biomass R&D was shifted in light of complementary funding in the 2002 Farm Bill, as well as a substantial number of non-mission supporting earmarks in the FY 2003 appropriations. Reductions in Industrial Technologies R&D result from recognition that the industrial sector is the most energy efficient sector of our economy, and industries, particularly energy-intensive industries, are succeeding in their attempts to be more energy efficient.

The Administration does not assume that outyear funding for the Hydrogen Fuel Initiative will come from cutting EERE, the Office of Science, or other programs. However, each year, the Administration may propose reallocations within its energy technology portfolio based on program performance, relative priority, expected potential for public benefits, alignment with the Administration's R&D investment criteria, and other factors.

Q3. In your discussion of the biomass program, you reference Congressional earmark levels as one reason why cuts are proposed for that program in the FY04 budget. However, roughly half of the cuts to the biomass program are proposed for the portion of the program funded through the Interior Appropriations account, which has never been significantly earmarked. What are the reasons for these proposed cuts?

A3. The Interior Appropriations reductions are all in one program—gasification technologies for forest and paper industry applications. Work in this area has progressed to the point where the private sector can complete it.

Q4. What role do you expect academic researchers to play in the hydrogen initiative? How much of the program will focus on basic research? How will the department pull together a basic research agenda that would contribute to the hydrogen initiative?

A4. Universities typically conduct a large portion of the Department's basic research. In the near-term, EERE anticipates a ramping up of efforts from universities for research on hydrogen storage. For example, a competitive solicitation will go out in three months. Basic research for which university capabilities are well suited include non-precious metal catalysts and high temperature polymer membranes for fuel cell systems, hydrogen storage materials, and high temperature materials critical to nuclear production of hydrogen. For example, on March 14, 2003, we conducted a hydrogen storage "Think Tank" meeting that included 10 university scientists to brainstorm breakthrough ideas that might solve the hydrogen storage issue. New projects are being planned that will include university participation beginning in FY 2004.

The Department is finalizing a broad research framework and a multi-year plan to support the successful implementation of the initiative. In addition to the office of Energy Efficiency and Renewable Energy, these efforts will include contributions from DOE's Offices of Science, Fossil Energy and Nuclear Energy, as well as the Department of Transportation.

Q5. How much of the budget request for the hydrogen initiative will be devoted toward the production of hydrogen with renewable energy, such as wind and solar power?

A5. Out of a total of $38.5 million for hydrogen production research in the FY 2004 Budget Request for the Hydrogen Fuel Initiative, $17.3 million is for research on the production of hydrogen with renewable energy.

Q6. Please provide for the record a copy of the Department's "well-to-wheels" analysis comparing hydrogen with other fuels and a copy of the study by the EIA of the impact on natural gas supplies and prices of using natural gas as a major source of hydrogen production.

A6. Copies of the Department's "well-to-wheels" analysis and the EIA study are attached.

ATTACHMENT

Assumptions for the Increased Penetration of Hydrogen Fuel Cell Technologies

Introduction

The assumptions provided below describe the inputs used to evaluate the impact of alternative scenarios regarding the increased penetration of hydrogen fueled proton-exchange membrane (PEM) fuel cells. These assumptions were used to emulate the scenarios provided by the Office of Energy Efficiency and Renewable Energy (EE). Four scenarios were constructed that differ from one another based on commercialization date (2011 or 2018) and whether there are production mandates for light duty vehicle manufacturers. Production mandates assume that light duty vehicle manufacturers are required to produce mainly fuel-cell vehicles, limiting their production of gasoline vehicles. This assumption was required to meet the penetration rates specified by EE. However, 100 percent penetration was not achievable by 2020 in the 2011 commercialization date scenario (see attached table). The four scenarios are:

- Commercialization in 2011 Without Production Mandates,
- Commercialization in 2018 Without Production Mandates,
- Commercialization in 2011 With Production Mandates, and
- Commercialization in 2018 With Production Mandates.

These cases assume that by the commercialization date (2011 or 2018), the increased research and development (R&D) provides a fuel cell stack at a cost that can be sold for $30 a kilowatt, reaching parity with the conventional gasoline vehicle. Where applicable, the cost reductions for PEM fuel cells and associated electronics are also captured in the other (non-transportation) demand sectors. The scenarios assume that other market conditioning (federal policies that encourage the development of a hydrogen infrastructure and auto manufacturer production of hydrogen fueled fuel cell vehicles) will be required for mass consumer acceptance of this technology (e.g., production mandates).

The National Energy Modeling System (NEMS) was used to estimate the impacts of introducing such fuel cells as a potential technology in end-use energy markets, based on the Annual Energy Outlook 2003 (AEO2003) Reference Case. The fuel cell system costs assumed for each sector are discussed below.

Detailed Assumptions

Transportation

In the transportation sector, a PEM fuel cell system cost vehicle is assumed to be at cost parity with a gasoline-powered vehicle by the date of commercialization.

Buildings

Performance characteristics and operating and maintenance (O&M) costs for fuel cells were assumed to improve over time as in the AEO2003 reference case. However, the installed cost per kilowatt (kW) for fuel cells available by the date of commercialization (2011 or 2018) was modified to correspond to the cost breakthroughs assumed for the fuel cell vehicle. Starting with the characteristics for the current 200 kW PEM fuel cell found in the National Renewable Energy Laboratory's (NREL) draft technology characterizations for fuel cell systems, the fuel stack cost was reduced to $20/kW, the thermal management component cost was reduced by $\frac{2}{3}$ to account for components already included in the "fuel cell engine" and for expected cost declines by commercialization date, and all other elements of the current installed cost were reduced by the same percentage as the cost decline between 2000 and the commercialization date in the AEO2003 reference case fuel cell characterization. The resulting cost for fuel cells installed in the buildings sectors was $1130/kW, 67 percent lower than the current PEM fuel cell cost and 34 percent lower than the installed cost in the AEO2003 reference case. The installed cost/kW was assumed to remain at the commercialization date level through 2025, unless the level of penetration resulted in lower costs due to technology learning, in which case further reductions would occur.

Industrial

For the industrial sector, the 10 megawatt (MW) gas turbine option in the combined heat and power (CHP) menu was replaced by a 10 MW fuel cell, with the cost and overall heat rate assumptions modified. The cost in 2000 was assumed to be $4600/kW, dropping to $500/kW by 2020.

Electricity Generators

In the reference case, fuel cell capital costs are assumed to decline from $2,137 per kilowatt in 2002 to $1,329 per kilowatt in 2017 and beyond. The heat rate is assumed to drop from 7,500 Btu per kilowatt-hour in 2002, to 6,750 Btu per kilowatt-hour over the next 10 years. Variable O&M costs are assumed to be two cents per kilowatt-hour, while fixed O&M costs are assumed to be $7.15 per kilowatt per year.

In the cases prepared for this analysis, capital costs were assumed to gradually decline from the initial $2137/kW in 2002 to $1347/kW in 2014, then steeply drop to $860/kW for the next five years, finally reaching $429/kW by 2020. The heat rate is assumed to be the same as reference case values through 2014, and then change to 7508 Btu/kWh through 2019, falling to 6826/kWh in 2020. Variable O&M costs are assumed to stay at the Reference case value of 20.44 mills per kilowatt-hour through 2014, and then fall to 5.19 mills per kilowatt-hour for 2015 and beyond.

Finally, fixed O&M costs are assumed to stay at the $7.15 per kilowatt-hour reference case value through 2014 and then rise to $14.18 for 2015 and beyond.

Impacts of Increased Penetration of Hydrogen Fuel Cell Technologies on Selected Energy Variables (all values for 2025 except GHG Intensity Change)

Variable	Reference	2018 Commercialization Date Without Production Mandates	2011 Commercialization Date Without Production Mandates	2018 Commercialization Date With Production Mandates[a]	2011 Commercialization Date With Production Mandates[1]
Fuel Cell Vehicle Sales (Thousands)	8.2	2328	2756	9762	15774
(Percent of Total Light Duty)	0.04	12.4	14.7	52.2	84.3
Fuel Cell Vehicle Stock (Millions)	0.04	11.36	25.38	36.13	168.23
(Percent of Total Light Duty)	0.01	3.8	8.5	12.1	56.4
Consumption					
Petroleum (mmbd)	29.17	28.75	28.13	27.87	22.63
(Percent Change From Reference)	--	-1.4	-3.6	-4.5	-22.4
Natural Gas (tcf)	34.93	35.48	35.78	35.91	38.20
(Percent Change From Reference)	--	1.6	2.4	2.8	9.4

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[a] Manufacturers will produce fuel cell vehicles and will be limited in the amount of non-fuel cell vehicles produced, especially gasoline.

Question submitted by Representative W. Todd Akin

Q1. *I have noticed in the FY04 budget request that DOE is requesting $17.3 million for renewables for hydrogen production. However, in the DOE's Hydrogen Energy Roadmap, you note that such methods as solar hear and photoelectrochemical electrolysis are still in early development stages. Do you feel that an investment of $17 million is the best use of scarce resources or do you feel that part of this money could be more appropriately used in other areas of hydrogen production such as natural gas?*

A1. DOE is dedicating $12.2 million for research on hydrogen production from natural gas, of which $6.5 million is for the Office of Fossil Energy's research on centralized production of natural gas, and $5.7 million for research in the Office of Energy Efficiency and Renewable Energy on decentralized hydrogen production.

Since one of the primary advantages of a hydrogen economy is the ability to produce hydrogen from a diverse array of domestic resources, this allocation represents a balance between near- and long-term research goals and among a portfolio of potential hydrogen production technologies.

In addition, large-scale centralized production of hydrogen from natural gas is the method currently used by industry to produce nine million tons of hydrogen each year. Some improvements to this methodology are within the industry's capability and interest.

Question submitted by Representative Gil Gutknecht

Q1. *In her testimony, Dr. Joan Ogden noted that wind turbines are a potential source for electrolytic hydrogen production. If we as a country are to move toward a hydrogen economy, we need to get serious about also increasing the amount of wind power we produce.*

Today, small wind systems are too expensive for most individuals to purchase, and the Federal Production Tax Credit for wind energy benefits only large cor-

porations. What changes would you suggest in the Federal Production Tax Credit, and/or what other ways can Congress promote the expansion of small-scale wind development? Moreover, what research is the Department planning to do on producing hydrogen from wind?

A1. Hydrogen can be produced from diverse domestic resources, including wind-generated electricity, using electrolyzers which split water molecules into hydrogen and oxygen. Our analysis has suggested that wind energy has the potential to produce a large volume of hydrogen from pathways that may include energy provided by large-scale wind farms as well as small-scale wind systems for distributed applications.

The Department's small wind systems activities are focused on reducing energy costs by developing technology and breaking down market barriers. Currently, the cost of energy from small wind turbines used in distributed power applications is in the range of 10 to 15 cents per kWh for Class 5 winds (13.4 to 14.3 mph average). The research goal of the Department's distributed wind technology program is to increase the efficiency of these turbines so that they will generate power at the same cost in lighter, more common, Class 3 winds (11.5 to 12.5 mph average).

The Department supports extension of the wind energy provision of the Federal Production Tax Credit (PTC), which applies to small business-use wind turbines, as proposed in the President's FY 2003 and FY 2004 budgets.

The Department of Energy is developing low-cost, high efficiency electrolyzers to enable cost competitive hydrogen production from electricity sources, including wind. Electrolyzer costs need to be reduced by a factor of over two for large systems and over three for small systems while maintaining or improving system efficiency. The Department has begun an analytic modeling project to investigate the viability of large and small-scale wind energy and electrolysis options, in the context of exploring infrastructure scenarios for hydrogen production, storage, and delivery.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Alan C. Lloyd, 2003 Chairman for the California Fuel Cell Partnership

Focus of the President's FreedomCAR and Hydrogen Initiatives

Q1. Should the President's FreedomCAR and Hydrogen Initiatives focus more on nearer-term applications, such as hybrid technologies, including diesel hybrids?

A1. As proposed by the President, the Department of Energy's vehicle research programs have an appropriate balance between research into technologies for the short-term and those for the longer-term. The U.S. should take advantage of the development and commercialization of extremely low emitting and high energy-efficiency technologies that, while they are not the ultimate goal, provide meaningful and substantial social benefits. FreedomCAR and the 21st Century Truck Initiative together make a $150 million investment in these advanced vehicle technologies, and their commercialization would provide significant near-term environmental and energy-efficiency rewards. At the same time, the President's proposal recognizes the need to take a longer-term view by fostering the continued development of fuel cell vehicle technologies (FCVs) and advanced fuels.

FCVs are considered by many to be the "holy grail" of vehicle technologies. They have the potential to eliminate vehicle pollution and greenhouse gas emissions, increase the Nation's energy security, and offer unique benefits to consumers (i.e., quiet operation, more electronic capabilities, etc.) FCVs are a long-term strategy that will not be commercially available at a cost-competitive price to individuals for several years (approximately ten years). The U.S. cannot ignore the need to continue a critical trend to reduce harmful vehicle emissions and increase energy efficiency while FCV technology matures.

Near-term technologies that advance the development of componentry for fuel cell vehicles include electric vehicles, hybrid electric vehicles, compressed natural gas and compressed natural gas hybrid electric vehicles, hydrogen internal combustion engine (ICE) and hydrogen ICE hybrid electric vehicles, and grid hybrid vehicles. These vehicle technologies also support the development and use of technologies and components that contribute to the commercialization of FCVs. The balance between the shorter-term and longer-term programs in the President's proposals seems to me to be the appropriate one.

Importance of the Involvement of Smaller Companies and International Manufacturers

Q2. In your experience, how important is it that the Administration involve smaller, technology-based companies, such as fuel cell manufacturers, in helping to shape the research agenda of these new initiatives? How about international manufacturers? What do such companies offer that the major domestic petroleum and auto companies are less able to?

A2. Our experience in California has been such that the smaller technology-based companies (manufacturers of fuel cells and hydrogen production technologies) have been the pioneers that are ready to make the vision of a hydrogen based economy successful. The U.S. will only benefit by including the input of smaller technology companies in shaping a research agenda and accelerating the path toward an energy solution that will eliminate harmful emissions and increase energy security.

The drive and experience of smaller companies is not limited to U.S. companies. In addition, the entire fuel cell industry is internationalizing rapidly, and the auto industry is already internationalized. The U.S. stands to benefit from the cost reductions resulting from competition between technology companies no matter where they are located, either corporate headquarters or manufacturing facilities.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Joan M. Ogden, Research Scientist, Princeton Environmental Institute

Impacts of Using Natural Gas as a Source of Hydrogen

Q1. Could you provide for the record your analysis of the impact on the natural gas market of using natural gas as a major source for producing hydrogen for transportation?

A1. As an extreme case, let's consider using hydrogen derived from natural gas to power *all* the light duty vehicles in the U.S., at projected 2020 levels of energy use. How does the required amount of natural gas compare to projections for total natural gas use?

We use as input, information on U.S. energy consumption from the latest USDOE Energy Information Agency Annual Energy Outlook,

http://www.eia.doe.gov/oiaf/aeo/index.html

http://www.eia.doe.gov/oiaf/aeo/supplement/sup_tran.pdf

What is the projected Energy Use in U.S. Light Duty Vehicles?

The energy use in all U.S. light duty vehicles (cars and light trucks) is estimated to be about 15.7 trillion BTU/year in 2002 growing to about 23.5 trillion BTU/year by 2020.

These projections are based on the following assumptions for the U.S.:

- Light-duty vehicle miles traveled are projected to grow by 2.4 percent per year from 2000 through 2020. (This is mostly a result of a growing number of vehicles.)
- New light-duty vehicle efficiency is projected to reach 25.6 miles per gallon by 2020. However, *the fleet average in-use fuel economy* (which determines actual fuel use) is projected to be 19.7 miles per gallon in 2002, and 19.8 miles per gallon in 2020.

How much energy would be needed if hydrogen was a major transportation fuel?

Based on calculations by our group and others, it appears that an efficient hydrogen fuel cell vehicle might have a fuel economy 3–4 times that of today's gasoline internal combustion engine vehicles. Our models indicate fuel economies of 82 miles per gallon equivalent for 4–5 passenger mid-size H_2 fuel cell vehicles, (and perhaps 80 percent of this for hydrogen internal combustion engine hybrids). (With further use of lightweight materials, studies by MIT and by our group suggest the fuel economy for a H_2 FCV could exceed 100 mpg.)

The total fuel consumption goes down as the fuel economy goes up. If the fuel economy for a hydrogen car is three times that of a reference gasoline car, then the energy use goes down by a factor of three (assuming each car drives the same number of miles per year). The EIA projects that future light duty vehicles will use 23.5 trillion BTU/y in 2020. If H_2 FCVs were used instead, the light duty vehicle hydrogen energy demand would be about one third of this or 7.8 trillion BTU/y [=(23.5 trillion BTU/yr)/3].

How much natural gas would be needed to make enough hydrogen for all U.S. light duty vehicles?

Natural gas can be converted to hydrogen at about 80 percent efficiency in large steam reformers. There is also electricity needed for compression of hydrogen for high-pressure storage on vehicles. Making the electricity requires additional energy, which might come from natural gas. Overall, for each 100 units of natural gas energy used (~82 units at the hydrogen plant and ~18 units to power electricity generation for compression) about 70 units of hydrogen energy would be available in the car's fuel tank. So, if 7.8 trillion BTU of H_2 would be needed to power the entire light duty vehicle sector, this would require about 11 trillion BTU of natural gas as input in 2020.

How does this compare to projected natural gas use?

Total demand for natural gas is projected to increase at an average annual rate of 1.8 percent between 2001 and 2020, from 22.7 trillion cubic feet to 34.9 trillion cubic feet, primarily because of rapid growth in demand for electricity generation. One trillion cubic feet of natural gas contains roughly 1 trillion BTU of energy.

So the natural gas needed to make enough H_2 for all light duty vehicles would increase natural gas use nationally in 2020 by a little less than one third = (11 trillion BTU/35 trillion BTU).

This is not a negligible amount of natural gas, but it does not represent a doubling or tripling of natural gas demand either.

Of course, not all vehicles will run on hydrogen by 2020. I just used this figure to make a point.

For a still optimistic but more reasonable, case, if 10 percent of all light duty vehicles used H_2 from natural gas in 2020, this would require about 1.1 trillion BTU of natural gas per year representing only about a three percent increase in projected natural gas use. For reference, we *already* use about this much natural gas to make hydrogen industrially today for refineries and chemical uses.

What are the prospects for using natural gas to make H_2?

Even for the very extreme assumption that all the light duty vehicles in the U.S. ran on hydrogen, the use of natural gas was increased by only about ⅓. For a more reasonable (but still quite optimistic) level of 10 percent H_2 light duty vehicles by 2020, the natural gas use is increased only three percent. This highlights that point that natural gas could be a very important transitional source for H_2 over the next several decades, without a huge impact on natural gas markets. As I mentioned in my earlier testimony, it is likely that hydrogen will be made from a variety of sources in the future, not just natural gas.

Evaluation of the Accuracy of Comparative Fuel Studies

Q2. Several well-to-wheels analyses have appeared recently comparing hydrogen to other fuels with conflicting results For example, the Argonne Labs study cited by the Department differed with the conclusions of the recently updated MIT study regarding the advantages of hydrogen powered vehicles over diesel hybrids How should policy-makers evaluate which of these highly technical studies is accurate, especially given the range of opinions in the literature?

A2. The differing results of various well-to-wheels studies are a result of the differing input assumptions. There is considerable uncertainty in some of the inputs (performance and cost of future vehicle components), and also considerable room for different approaches to vehicle design, that could give differing relative fuel economies of H_2 vehicles versus diesel hybrids, for example. These factors explain why the results from two studies can seem contradictory, yet each is correct for the particular set of assumptions adopted by the researcher.

Most well-to-wheels studies I have examined are broadly consistent (to within the uncertainty of the results) on several issues:

- It should be possible to improve *fuel economy* of gasoline internal combustion engine vehicles by a factor of 1.5–2 compared to today's gasoline cars, with improvements like lightweight materials, streamlining and hybrid drive trains.
- The well-to-wheel emissions of *greenhouse gases* can be significantly reduced as compared to today's vehicles (by perhaps 50 percent) by adopting advanced gasoline or diesel internal combustion vehicles.
- The well-to-wheels *primary energy use* for advanced H_2 vehicles (H_2 fuel cells or H_2 ICE hybrids) is similar to that for a gasoline or diesel hybrid. Unlike gasoline or diesel, the hydrogen can be made from a variety of sources.
- Compared to diesel or gasoline hybrids, H_2 vehicles have similar well-to-wheels *greenhouse gas emissions* when hydrogen is made from natural gas, but much lower emissions when H_2 is made from decarbonized fossil sources (H_2 from natural gas or coal with CO_2 sequestration) or from renewables (wind, biomass, solar).

Given the uncertainties in the inputs, seeming contradictions among these studies are often "within the bounds of uncertainty." Rather than choosing one of these studies, as most accurate, it behooves policy-makers to understand that there are gains to be made, but the precise amount is not exactly known now. It is important that managers of the programs in the DOE understand the differences among these studies (I think they do), and to look for areas where R&D might have an impact in improving vehicle performance or reducing emissions or cost.

There is also an issue of *when* a given vehicle technology could be ready to help deal with environmental and energy supply problems. It will be a while before hydrogen could be widely used, but cleaner, more efficient internal combustion engine technologies (like hybrids) could be widely used in the interim, while hydrogen is being developed.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Lawrence D. Burns, Vice President, Research Development and Planning, General Motors

Availability of Fuel Cell Vehicles to Consumers

Q1. In your testimony, you state that GM has made a commitment to having fuel cell vehicles for sale by 2010. Will these vehicles be offered for sale to a limited market, similar to the programs Toyota and Honda have in place today, or will they be available for the average consumer at competitive prices in the mass market?

A1. Hydrogen fuel cell vehicles must realize a significant share of the global auto market to yield beneficial energy and environmental impacts. As such, they must be as affordable as today's vehicles, sustainable from an environmental and energy perspective, compelling from a design and value standpoint, and profitable (to attract capital to grow capacity). GM is working hard and committing significant resources to realize these criteria as soon as possible.

Our goal is to be the first auto company to profitably build and sell one million fuel cell vehicles. We believe this is possible by the middle of the next decade. As an interim stretch goal, we are targeting to have the capability of building an affordable (to the average customer) and compelling fuel cell vehicle by 2010. The primary motivation for us to meet the 2010 date is the significant business growth opportunity resulting from reinventing the automobile around fuel cells, electric drive, by-wire controls, and hydrogen.

The two toughest technical challenges to meeting our 2010 stretch goal are the cost of the fuel cell propulsion module and how best to store hydrogen on-board the vehicle. Realizing our 2010 goal requires us to overcome these challenges. While we are determined to do just that, the inherent risks and uncertainties associated with developing new technologies means you should view our plans as goals, rather than commitments.

Having affordable and compelling vehicles is an important necessary condition for generating high demand for fuel cell vehicles. However, conveniently available and competitively priced hydrogen is also an important condition. Vehicle affordability will also be directly affected by a number of government policies, including federal tax policy towards fuel cell vehicles and hydrogen, and the resolution of a number of issues related to codes and standards. Other government policies can have a more indirect effect on vehicle affordability, including the level of support for federal research into fuel cells and hydrogen storage, and early procurement by federal agencies of fuel cell vehicles as well as stationary fuel cells.

Appendix 2:

ADDITIONAL MATERIAL FOR THE RECORD

Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles

Final Report

Phase II Final Deliverable to
DOE

February 6, 2002

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390

35340-00

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Table of Contents

DOE has commissioned this study to support target setting and progress monitoring for its direct hydrogen fuel cell vehicle program.

- DOE Office of Transportation Technologies (OTT) supports proton exchange membrane fuel cells (PEMFCs) for transportation applications:
  - Focus since 1992 on on-board reforming of gasoline and other fuels
  - DOE/OTT is currently developing a direct hydrogen Fuel Cell Vehicle (FCV) program in coordination with DOE's Hydrogen Program
- DOE has commissioned this study to help set targets for its direct hydrogen program:
  - Targets are being set by comparison of direct hydrogen FCVs with alternative fuel and powertrain options
  - Consider energy efficiency, greenhouse gas emissions, cost, and safety
  - Include methanol, ethanol, diesel, and gasoline fuels but focus on hydrogen
  - Include internal combustion engine vehicles and battery electric vehicles for comparison

Outline

Main Report

- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- Cost
- Safety
- Conclusion & DOE Target Setting

Details on pages:
A18-20, 73-75,
106-118

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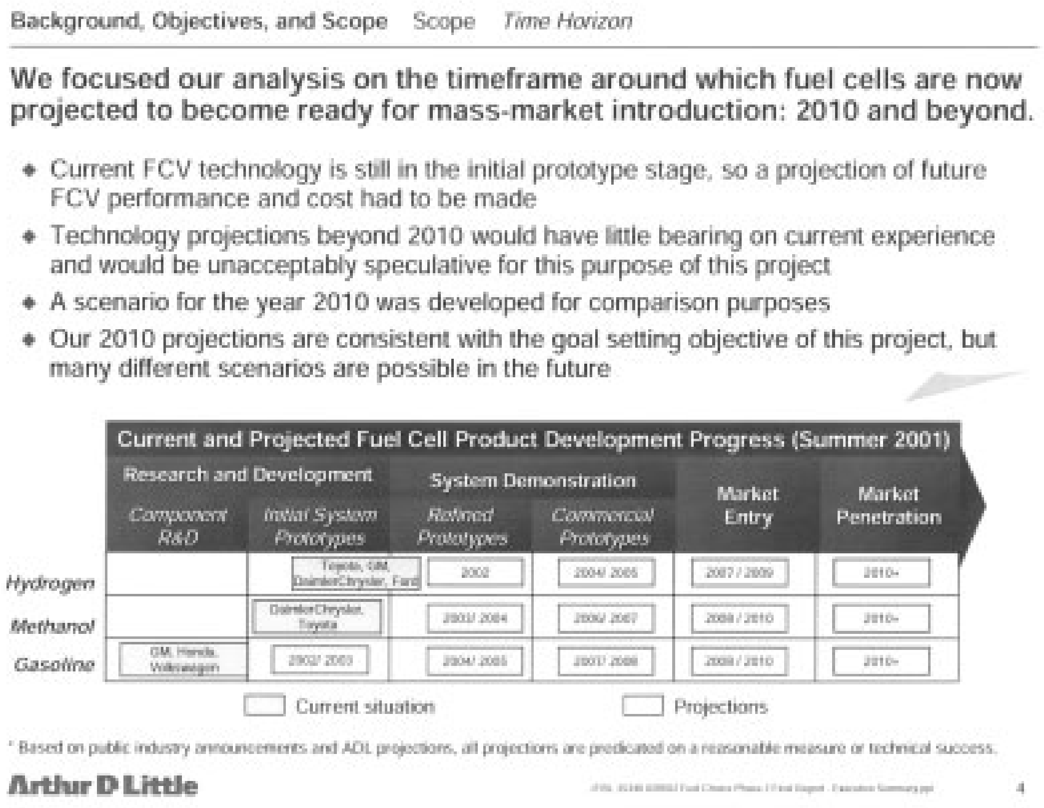
  - Targets are being set by comparison of direct hydrogen FCVs with alternative fuel and powertrain options
  - In Phase I, Arthur D. Little provided initial targets for hydrogen FCVs based on quick estimates and readily available information



We focused our analysis on the timeframe around which fuel cells are now projected to become ready for mass-market introduction: 2010 and beyond.

- Current FCV technology is still in the initial prototype stage, so a projection of future FCV performance and cost had to be made
- Technology projections beyond 2010 would have little bearing on current experience and would be unacceptably speculative for this purpose of this project
- A scenario for the year 2010 was developed for comparison purposes
- Our 2010 projections are consistent with the goal setting objective of this project, but many different scenarios are possible in the future

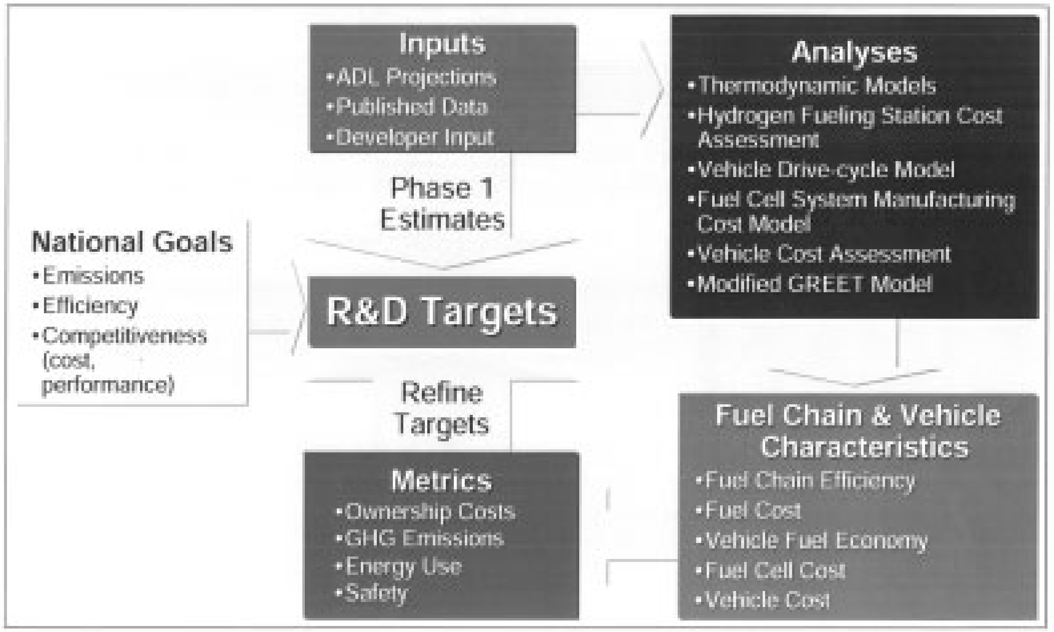
Current and Projected Fuel Cell Product Development Progress (Summer 2001)

	Research and Development		System Demonstration		Market Entry	Market Penetration
	Component R&D	*Initial System Prototypes*	*Refined Prototypes*	*Commercial Prototypes*		
Hydrogen		Toyota, GM, DaimlerChrysler, Ford	2002	2004/ 2005	2007 / 2009	2010+
Methanol		DaimlerChrysler, Toyota	2003/ 2004	2006/ 2007	2008 / 2010	2010+
Gasoline	GM, Honda, Volkswagen	2002/ 2003	2004/ 2005	2007/ 2008	2008 / 2010	2010+

▨ Current situation ☐ Projections

* Based on public industry announcements and ADL projections, all projections are predicated on a reasonable measure or technical success.

Combining a variety of inputs through thorough analyses, we are able to develop meaningful and defensible guidelines for R&D targets.



National Goals
- Emissions
- Efficiency
- Competitiveness (cost, performance)

Inputs
- ADL Projections
- Published Data
- Developer Input

Phase 1 Estimates

R&D Targets

Refine Targets

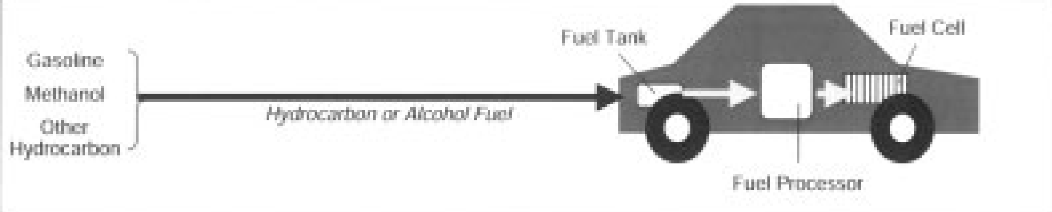
Metrics
- Ownership Costs
- GHG Emissions
- Energy Use
- Safety

Analyses
- Thermodynamic Models
- Hydrogen Fueling Station Cost Assessment
- Vehicle Drive-cycle Model
- Fuel Cell System Manufacturing Cost Model
- Vehicle Cost Assessment
- Modified GREET Model

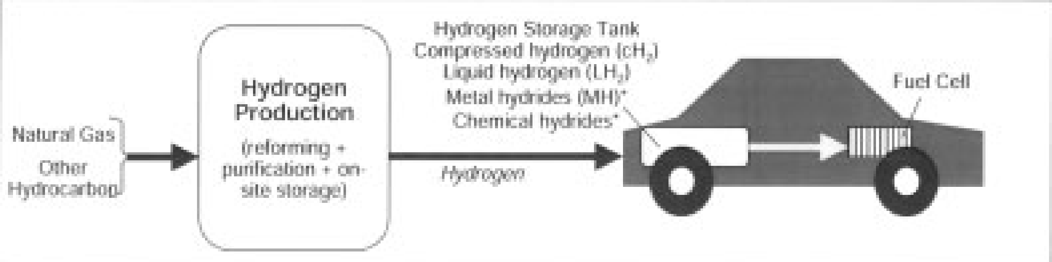
Fuel Chain & Vehicle Characteristics
- Fuel Chain Efficiency
- Fuel Cost
- Vehicle Fuel Economy
- Fuel Cell Cost
- Vehicle Cost

Fundamentally, two strategies may be followed for fueling PEM fuel cell vehicles (FCVs): on-board reforming and off-board hydrogen production.

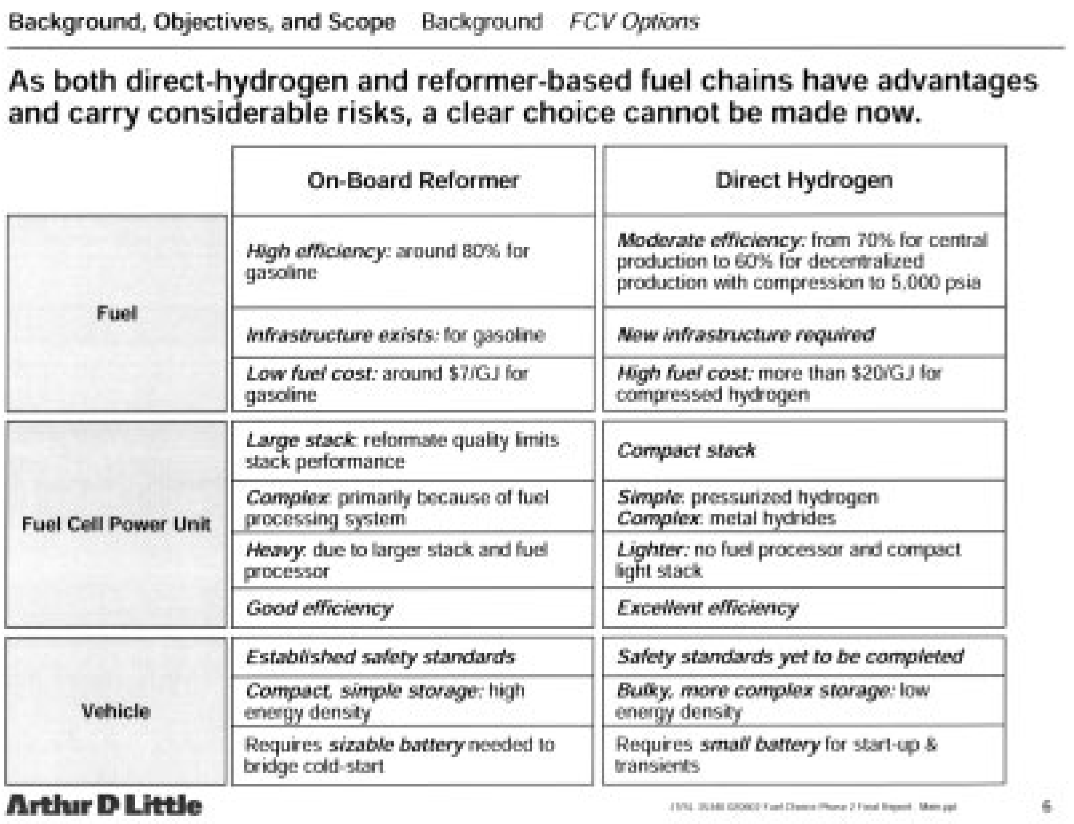
On-Board Reforming (Reformer-Based Vehicle)



Direct Hydrogen: (off-board hydrogen production)



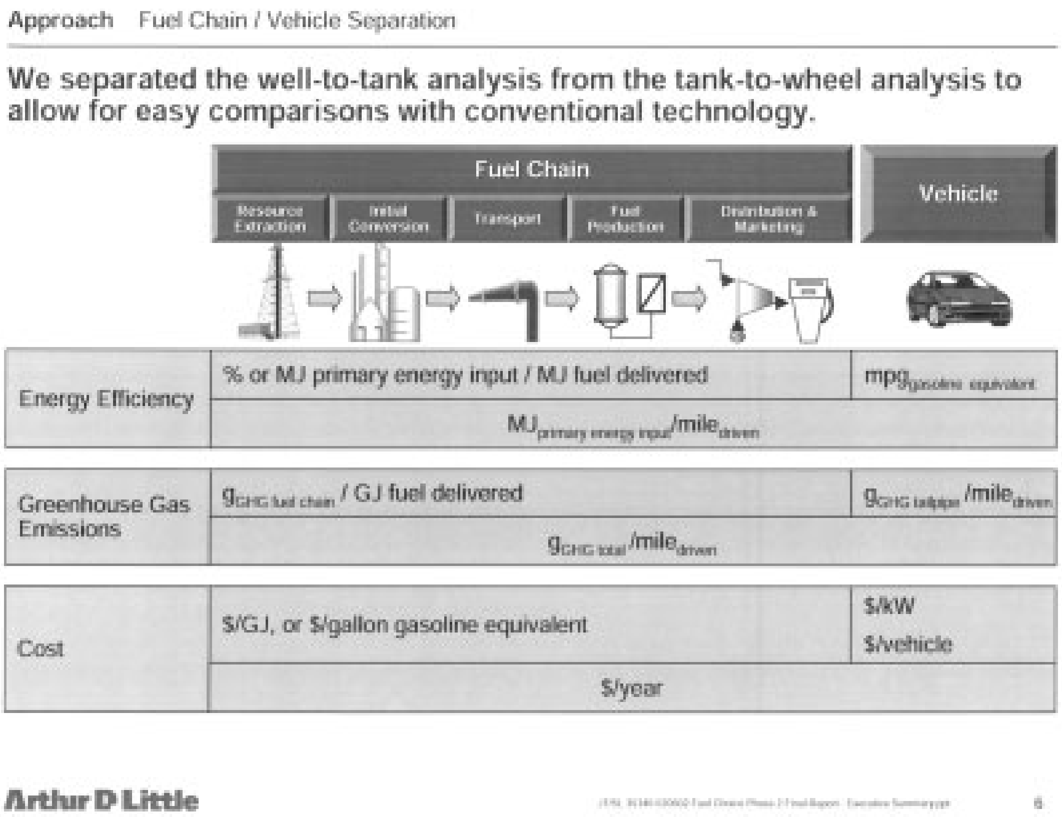
* Modest processing may be needed for these hydrogen storage options but the product is pure hydrogen.



As both direct-hydrogen and reformer-based fuel chains have advantages and carry considerable risks, a clear choice cannot be made now.

	On-Board Reformer	Direct Hydrogen
Fuel	***High efficiency:*** around 80% for gasoline	***Moderate efficiency:*** from 70% for central production to 60% for decentralized production with compression to 5,000 psia
	Infrastructure exists: for gasoline	***New infrastructure required***
	Low fuel cost: around $7/GJ for gasoline	***High fuel cost:*** more than $20/GJ for compressed hydrogen
Fuel Cell Power Unit	***Large stack:*** reformate quality limits stack performance	***Compact stack***
	Complex: primarily because of fuel processing system	***Simple:*** pressurized hydrogen ***Complex:*** metal hydrides
	Heavy: due to larger stack and fuel processor	***Lighter:*** no fuel processor and compact light stack
	Good efficiency	***Excellent efficiency***
Vehicle	***Established safety standards***	***Safety standards yet to be completed***
	Compact, simple storage: high energy density	***Bulky, more complex storage:*** low energy density
	Requires ***sizable battery*** needed to bridge cold-start	Requires ***small battery*** for start-up & transients

Arthur D Little



Approach Fuel Chain / Vehicle Separation

We separated the well-to-tank analysis from the tank-to-wheel analysis to allow for easy comparisons with conventional technology.

Fuel Chain

Resource Extraction → Initial Conversion → Transport → Fuel Production → Distribution & Marketing

Vehicle

	Fuel Chain	Vehicle
Energy Efficiency	% or MJ primary energy input / MJ fuel delivered	$mpg_{gasoline\ equivalent}$
	$MJ_{primary\ energy\ input}/mile_{driven}$	
Greenhouse Gas Emissions	$g_{GHG\ fuel\ chain}$ / GJ fuel delivered	$g_{GHG\ tailpipe}/mile_{driven}$
	$g_{GHG\ total}/mile_{driven}$	
Cost	$/GJ, or $/gallon gasoline equivalent	$/kW $/vehicle
	$/year	

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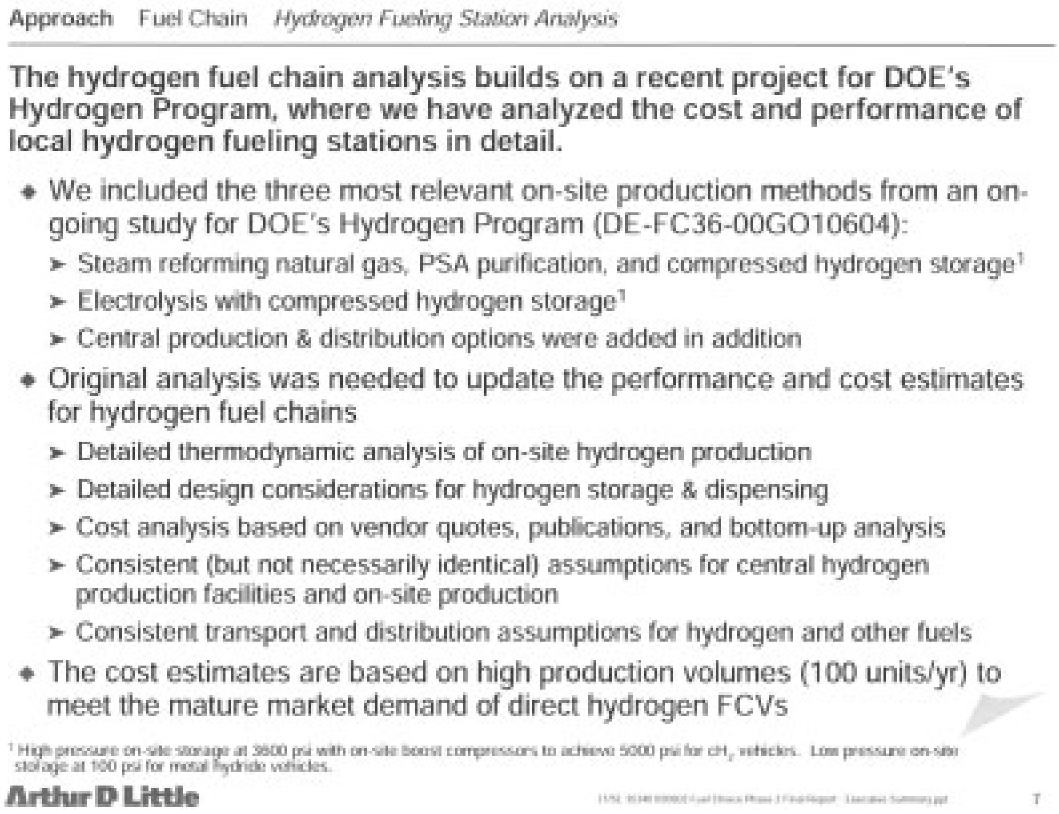

The hydrogen fuel chain analysis builds on a recent project for DOE's Hydrogen Program, where we have analyzed the cost and performance of local hydrogen fueling stations in detail.

- We included the three most relevant on-site production methods from an on-going study for DOE's Hydrogen Program (DE-FC36-00GO10604):
  - Steam reforming natural gas, PSA purification, and compressed hydrogen storage[1]
  - Electrolysis with compressed hydrogen storage[1]
  - Central production & distribution options were added in addition
- Original analysis was needed to update the performance and cost estimates for hydrogen fuel chains
  - Detailed thermodynamic analysis of on-site hydrogen production
  - Detailed design considerations for hydrogen storage & dispensing
  - Cost analysis based on vendor quotes, publications, and bottom-up analysis
  - Consistent (but not necessarily identical) assumptions for central hydrogen production facilities and on-site production
  - Consistent transport and distribution assumptions for hydrogen and other fuels
- The cost estimates are based on high production volumes (100 units/yr) to meet the mature market demand of direct hydrogen FCVs

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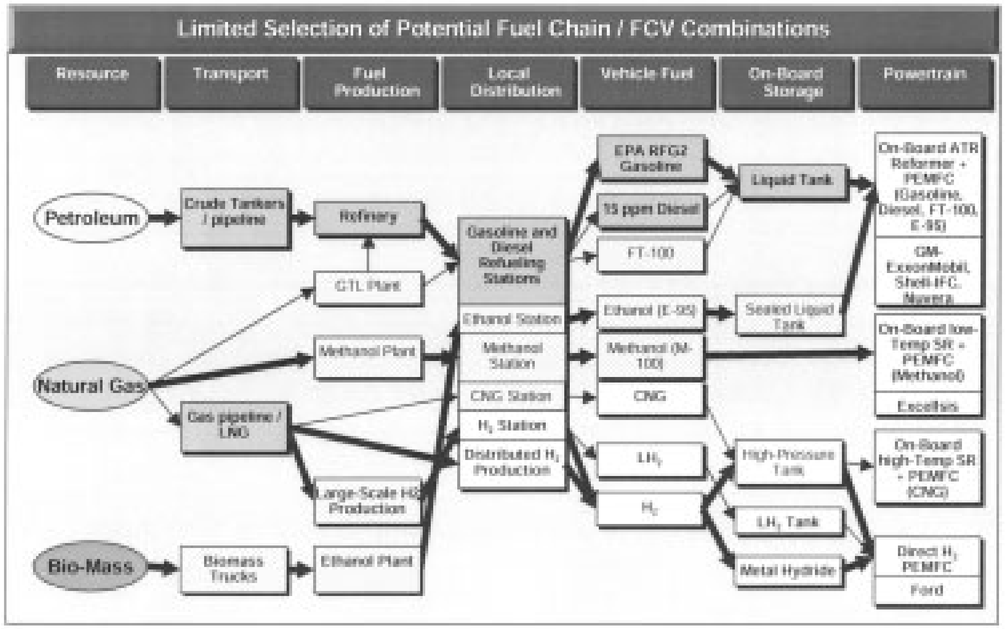
[1] High pressure on-site storage at 3600 psi with on-site boost compressors to achieve 5000 psi for cH_2 vehicles. Low pressure on-site storage at 100 psi for metal hydride vehicles.

A very large number of potential fuel chains and vehicle architectures can be and are being considered for fueling fuel cell vehicles.



Limited Selection of Potential Fuel Chain / FCV Combinations

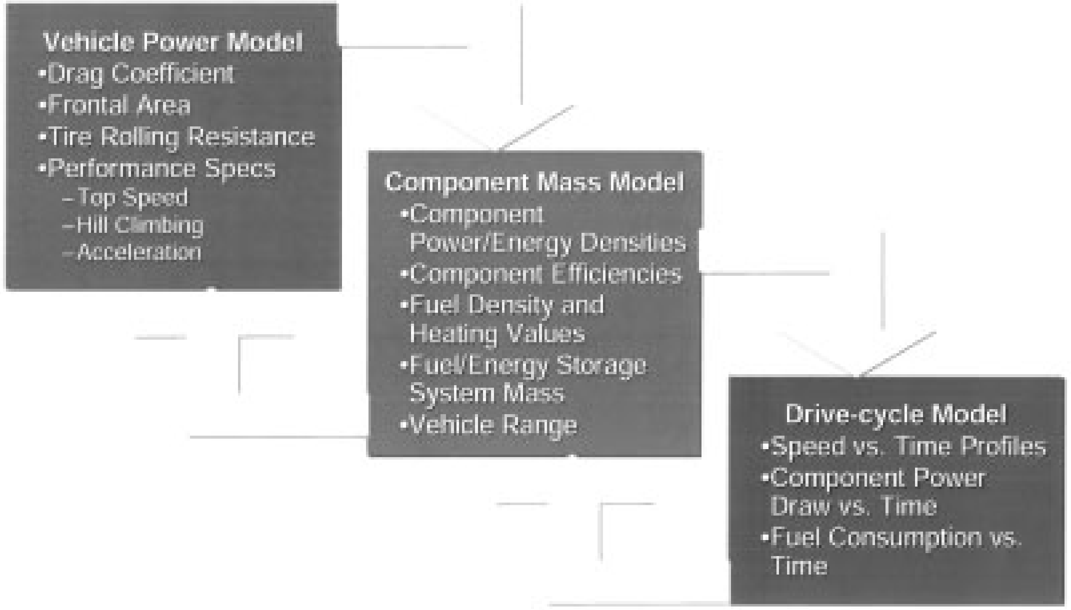
Resource
Transport
Fuel Production
Local Distribution
Vehicle Fuel
On-Board Storage
Powertrain

Petroleum
Natural Gas
Bio-Mass
Crude Tankers / pipeline
Gas pipeline / LNG
Biomass Trucks
Refinery
GTL Plant
Methanol Plant
Large-Scale H2 Production
Ethanol Plant
Gasoline and Diesel Refueling Stations
Ethanol Station
Methanol Station
CNG Station
H_2 Station
Distributed H_2 Production
EPA RFG2 Gasoline
15 ppm Diesel
FT-100
Ethanol (E-95)
Methanol (M-100)
CNG
LH_2
H_2
Liquid Tank
Sealed Liquid Tank
High-Pressure Tank
LH_2 Tank
Metal Hydride
On-Board ATR Reformer + PEMFC (Gasoline, Diesel, FT-100, E-95)
GM-ExxonMobil, Shell-IFC, Nuvera
On-Board low-Temp SR + PEMFC (Methanol)
Excellsis
On-Board high-Temp SR + PEMFC (CNG)
Direct H_2 PEMFC
Ford

DOE asked ADL to assess the implications of different fueling and powertrain options on vehicle efficiency, CO_2 emissions, cost, and safety.

- The overall goals (stated above) for all three Phases are the same
- The specific objectives for this Phase II are to refine DOE's R&D targets for its direct hydrogen FCV program by comparing them with a range of other powertrains:
  - Consider energy efficiency, greenhouse gas emissions, cost, and safety
  - Include methanol, ethanol, diesel, and gasoline fuels but focus on hydrogen
  - Include internal combustion engine vehicles and battery electric vehicles for comparison
- In Phase III the assessment will be refined in two important ways:
  - More detailed assessment of impacts on the existing fueling infrastructure will be made
  - Additional fuel chains will be considered if appropriate
  - The risk (including financial risk) of developing each of the pathways will be estimated (as opposed to assessing the "end-state" which was done in Phase II)

We used a simple vehicle drive-cycle simulation model to estimate fuel economy and power requirements for each powertrain.



Vehicle Power Model
- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model
- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

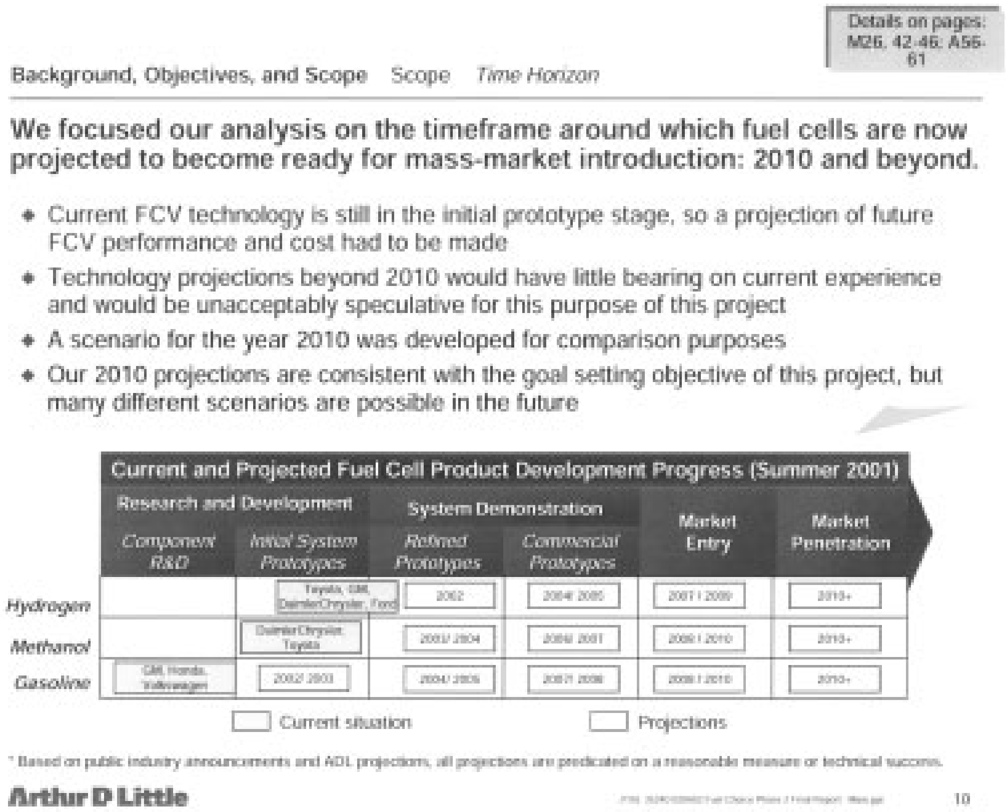
Drive-cycle Model
- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

Our FCV power unit analysis builds on ongoing ADL/DOE analysis of automotive fuel cell systems.

- In an ongoing program for DOE (DE-SCO2-98EE50526), ADL has developed a detailed cost and performance model for an on-board ATR FCV power unit
  - Model developed in conjunction with ANL, with feedback from OTT and PNGV
  - Assumes high production volumes but uses near-term performance inputs
- We have modified the model to estimate component costs and weights for scenarios of future performance
  - ADL, "Cost Analysis of Fuel Cell System for Transportation – Pathways to Low Cost", 2001 Final Report, prepared for DOE, to be published in 2002
  - High temperature membranes, increased power density, and improvements in fuel processor catalysts and other materials
  - These assumptions reflect a best-case scenario of success in current R&D activities, but do not project future technology leaps
- We have also developed future performance scenarios for for methanol, ethanol, and direct hydrogen vehicles
  - Based on in-house kinetic and thermodynamic calculations
- The model cost estimates are based on high production volumes (500,000 units/yr) that will not likely be possible in the 2010 timeframe

This phase has six specific objectives to help achieve the overall goal, each related to a comparison of hydrogen with other FCV fuel choices.

Task	Objective	Description
1	Refine well-to-tank fuel chain model	• Refine performance calculations for hydrogen and compare them with gasoline, diesel, CNG, ethanol, and methanol
2	Fuel cost assessment	• Determine fuel price projections for all fuels, focusing on hydrogen fuel chains
3	Develop tank-to-wheel vehicle model	• Develop detailed vehicle performance calculations for direct hydrogen and gasoline-fueled FCVs
4	Vehicle ownership cost assessment	• Compare direct hydrogen FCV ownership costs with other FCVs, electric vehicles, and conventional vehicles
5	Safety analysis	• Identify major safety concerns and perform a safety issues analysis on all fuel chains and vehicle options
6	Prepare final report	• Prepare final report summarizing our approach and final results to be reviewed by DOE and industry



Details on pages: M26, 42-46; A56-61

Background, Objectives, and Scope Scope *Time Horizon*

We focused our analysis on the timeframe around which fuel cells are now projected to become ready for mass-market introduction: 2010 and beyond.

- Current FCV technology is still in the initial prototype stage, so a projection of future FCV performance and cost had to be made
- Technology projections beyond 2010 would have little bearing on current experience and would be unacceptably speculative for this purpose of this project
- A scenario for the year 2010 was developed for comparison purposes
- Our 2010 projections are consistent with the goal setting objective of this project, but many different scenarios are possible in the future

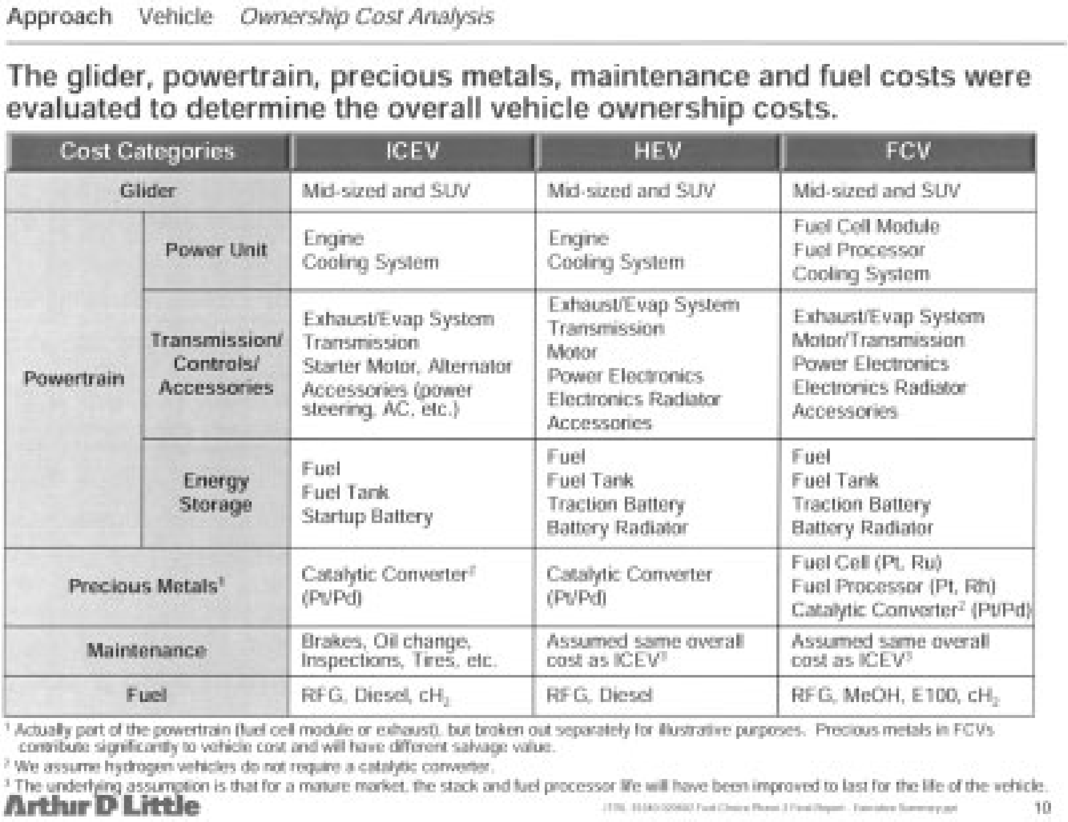
Current and Projected Fuel Cell Product Development Progress (Summer 2001)

	Research and Development		System Demonstration		Market Entry	Market Penetration
	Component R&D	*Initial System Prototypes*	*Refined Prototypes*	*Commercial Prototypes*		
Hydrogen		Toyota, GM, DaimlerChrysler, Ford	2002	2004/ 2005	2007 / 2009	2010+
Methanol		DaimlerChrysler, Toyota	2003/ 2004	2006/ 2007	2009 / 2010	2010+
Gasoline	GM, Honda, Volkswagen	2002/ 2003	2004/ 2005	2007/ 2008	2009 / 2010	2010+

☐ Current situation ☐ Projections

* Based on public industry announcements and ADL projections, all projections are predicated on a reasonable measure or technical success.

Arthur D Little 10



Approach Vehicle *Ownership Cost Analysis*

The glider, powertrain, precious metals, maintenance and fuel costs were evaluated to determine the overall vehicle ownership costs.

Cost Categories		ICEV	HEV	FCV
Glider		Mid-sized and SUV	Mid-sized and SUV	Mid-sized and SUV
Powertrain	**Power Unit**	Engine Cooling System	Engine Cooling System	Fuel Cell Module Fuel Processor Cooling System
	Transmission/ Controls/ Accessories	Exhaust/Evap System Transmission Starter Motor, Alternator Accessories (power steering, AC, etc.)	Exhaust/Evap System Transmission Motor Power Electronics Electronics Radiator Accessories	Exhaust/Evap System Motor/Transmission Power Electronics Electronics Radiator Accessories
	Energy Storage	Fuel Fuel Tank Startup Battery	Fuel Fuel Tank Traction Battery Battery Radiator	Fuel Fuel Tank Traction Battery Battery Radiator
Precious Metals[1]		Catalytic Converter[2] (Pt/Pd)	Catalytic Converter (Pt/Pd)	Fuel Cell (Pt, Ru) Fuel Processor (Pt, Rh) Catalytic Converter[2] (Pt/Pd)
Maintenance		Brakes, Oil change, Inspections, Tires, etc.	Assumed same overall cost as ICEV[3]	Assumed same overall cost as ICEV[3]
Fuel		RFG, Diesel, cH_2	RFG, Diesel	RFG, MeOH, E100, cH_2

[1] Actually part of the powertrain (fuel cell module or exhaust), but broken out separately for illustrative purposes. Precious metals in FCVs contribute significantly to vehicle cost and will have different salvage value.

[2] We assume hydrogen vehicles do not require a catalytic converter.

[3] The underlying assumption is that for a mature market, the stack and fuel processor life will have been improved to last for the life of the vehicle.

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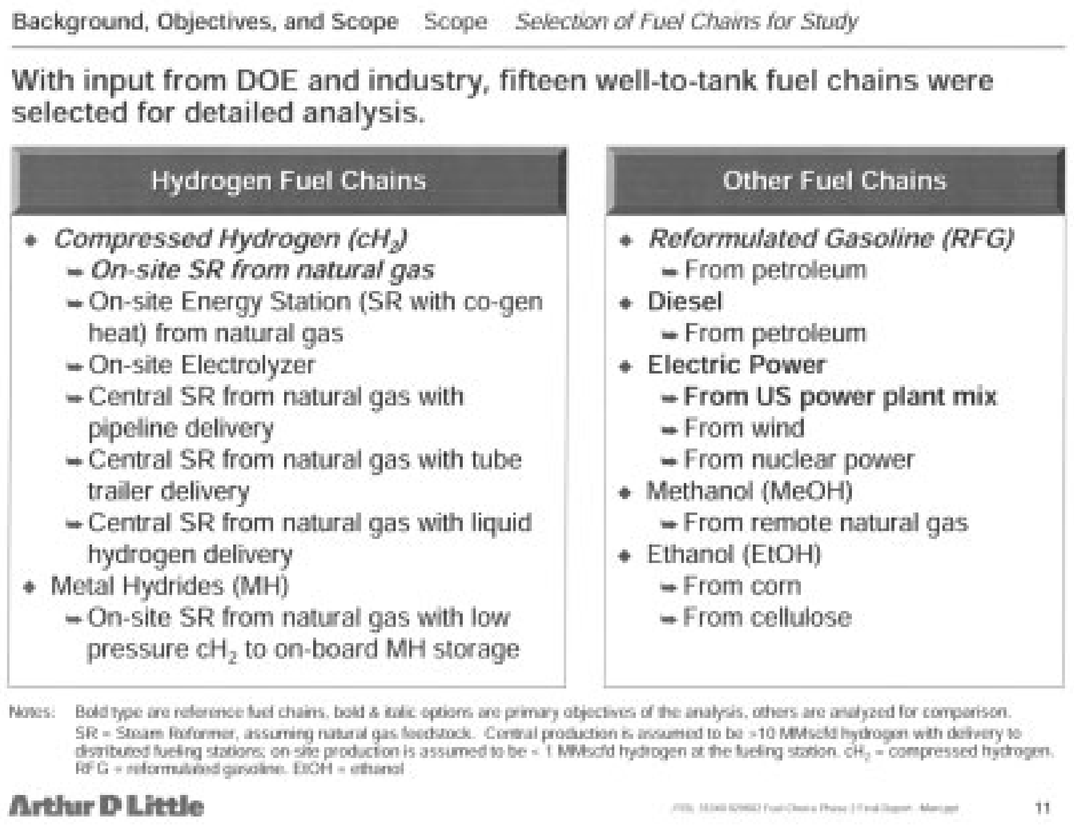
10

None of the alternative fuels can be delivered with greater primary energy conversion efficiency than conventional fuels.

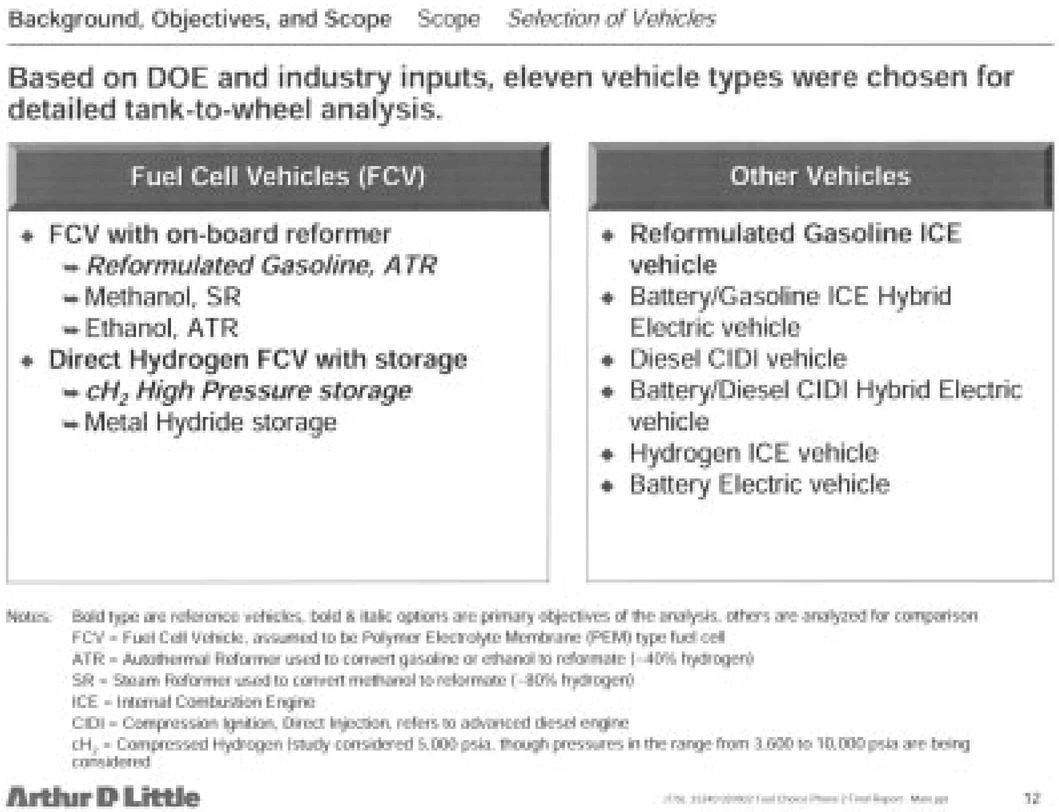
- The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel
    - Oil refineries provide unparalleled primary fuel conversion efficiencies of ~85%
    - Syngas production from natural gas (as needed in the production of hydrogen and methanol) imposes an additional penalty of roughly 15% on these fuel chains
    - Extensive use of electric power penalizes energy efficiency even more significantly, making electrolysis chains over 3 times more energy intensive than hydrogen from on-site NG reformers, and almost 4 times more than gasoline
- Biomass-based conversion chains (ethanol) have fuel chain efficiencies below 50%, though much of this primary energy may be renewable
- Due to their high energy density, the primary energy use for transport and distribution of conventional fuels is the lowest
    - Transport and distribution comprise less than 5% of energy use for petroleum fuels
    - Alcohol fuels have roughly half the energy density of hydrocarbon fuels, and hence transportation energy use is roughly double that of conventional fuels
    - Energy use for the compression, liquefaction, or hydrate formation associated with hydrogen transport & vehicle storage adds 10-30% to primary energy use



With input from DOE and industry, fifteen well-to-tank fuel chains were selected for detailed analysis.

Hydrogen Fuel Chains	Other Fuel Chains
◆ *Compressed Hydrogen (cH_2)* ➥ ***On-site SR from natural gas*** ➥ On-site Energy Station (SR with co-gen heat) from natural gas ➥ On-site Electrolyzer ➥ Central SR from natural gas with pipeline delivery ➥ Central SR from natural gas with tube trailer delivery ➥ Central SR from natural gas with liquid hydrogen delivery ◆ Metal Hydrides (MH) ➥ On-site SR from natural gas with low pressure cH_2 to on-board MH storage	◆ ***Reformulated Gasoline (RFG)*** ➥ From petroleum ◆ **Diesel** ➥ From petroleum ◆ **Electric Power** ➥ **From US power plant mix** ➥ From wind ➥ From nuclear power ◆ Methanol (MeOH) ➥ From remote natural gas ◆ Ethanol (EtOH) ➥ From corn ➥ From cellulose

Notes: Bold type are reference fuel chains, bold & italic options are primary objectives of the analysis, others are analyzed for comparison.
SR = Steam Reformer, assuming natural gas feedstock. Central production is assumed to be >10 MMscfd hydrogen with delivery to distributed fueling stations; on-site production is assumed to be < 1 MMscfd hydrogen at the fueling station. cH_2 = compressed hydrogen. RFG = reformulated gasoline. EtOH = ethanol

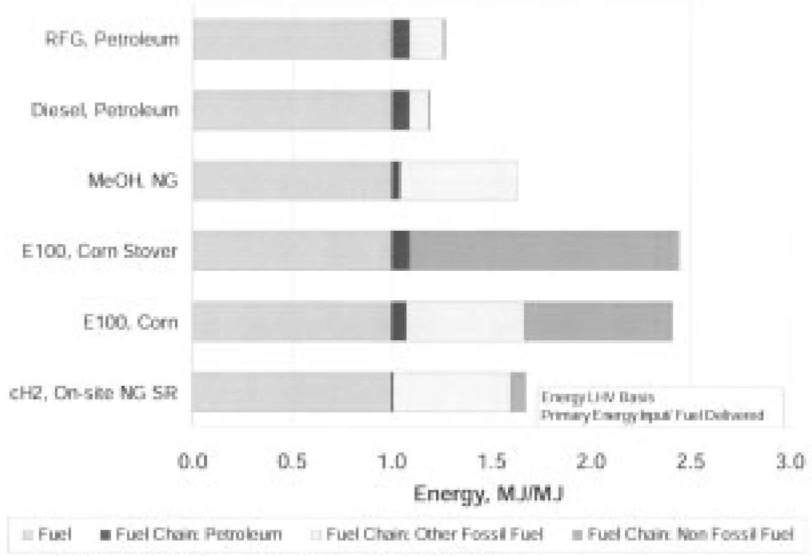


Based on DOE and industry inputs, eleven vehicle types were chosen for detailed tank-to-wheel analysis.

Fuel Cell Vehicles (FCV)	Other Vehicles
- FCV with on-board reformer – ***Reformulated Gasoline, ATR*** – Methanol, SR – Ethanol, ATR - **Direct Hydrogen FCV with storage** – ***cH_2 High Pressure storage*** – Metal Hydride storage	- **Reformulated Gasoline ICE vehicle** - Battery/Gasoline ICE Hybrid Electric vehicle - Diesel CIDI vehicle - Battery/Diesel CIDI Hybrid Electric vehicle - Hydrogen ICE vehicle - Battery Electric vehicle

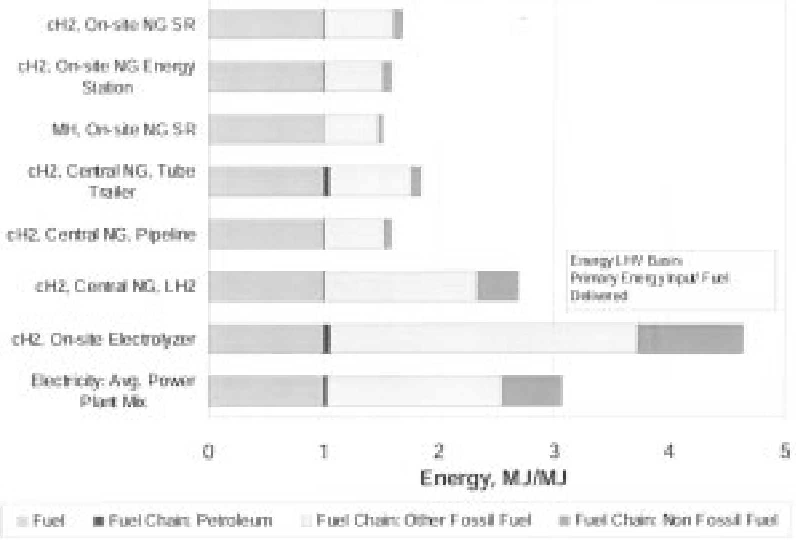
Notes: Bold type are reference vehicles, bold & italic options are primary objectives of the analysis, others are analyzed for comparison
FCV = Fuel Cell Vehicle, assumed to be Polymer Electrolyte Membrane (PEM) type fuel cell
ATR = Autothermal Reformer used to convert gasoline or ethanol to reformate (~40% hydrogen)
SR = Steam Reformer used to convert methanol to reformate (~80% hydrogen)
ICE = Internal Combustion Engine
CIDI = Compression Ignition, Direct Injection, refers to advanced diesel engine
cH_2 = Compressed Hydrogen (study considered 5,000 psia, though pressures in the range from 3,600 to 10,000 psia are being considered

The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel



* Net E100 energy use include byproduct credits, as do petroleum products.

Steam reforming-based hydrogen production provides the most efficient options for hydrogen generation, especially in a co-generation context;...



* Electrolyzer energy consumption assumes a US average mix of grid power.

... liquid hydrogen and electrolysis options use far more energy.

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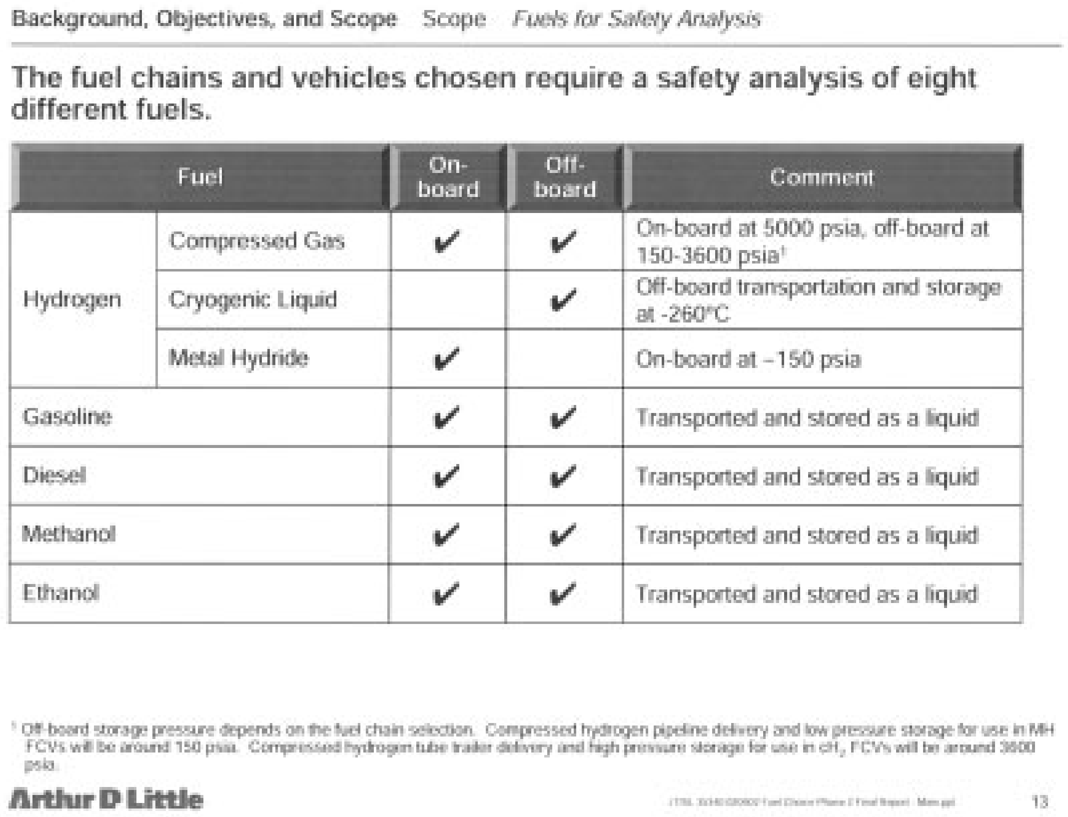
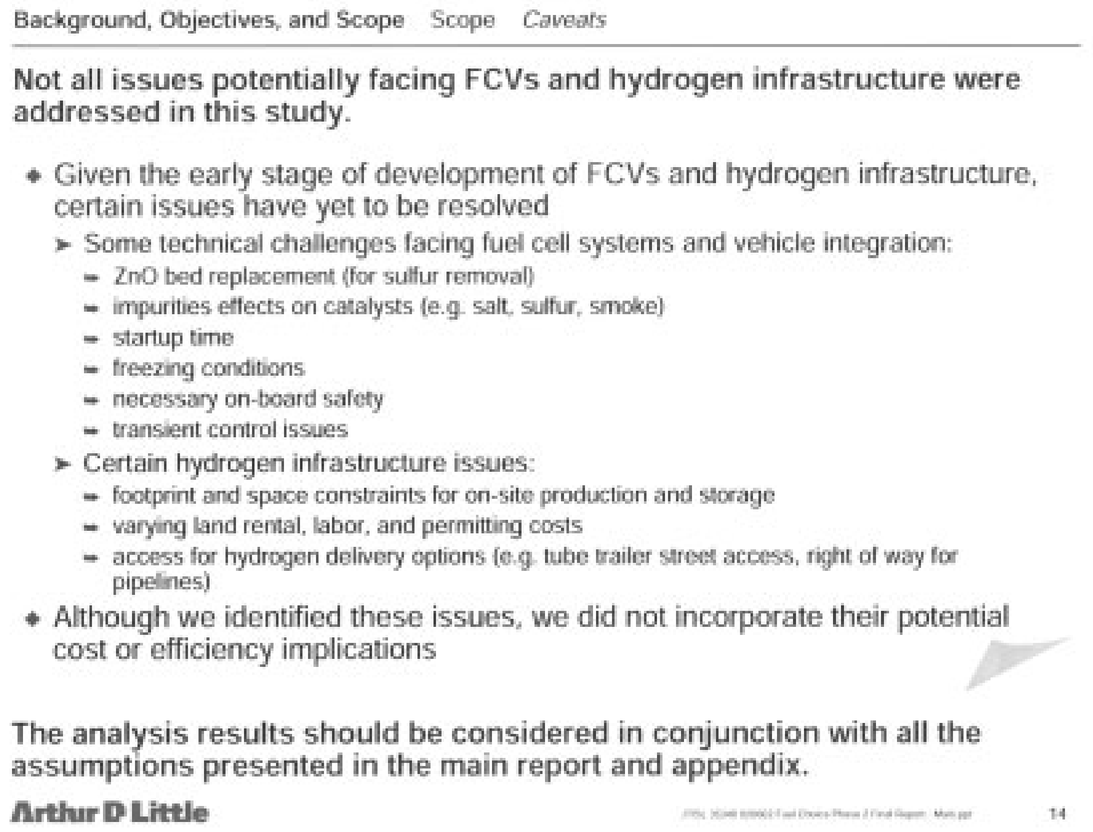


Background, Objectives, and Scope Scope *Fuels for Safety Analysis*

The fuel chains and vehicles chosen require a safety analysis of eight different fuels.

Fuel		On-board	Off-board	Comment
Hydrogen	Compressed Gas	✓	✓	On-board at 5000 psia, off-board at 150-3600 psia[1]
	Cryogenic Liquid		✓	Off-board transportation and storage at -260°C
	Metal Hydride	✓		On-board at ~150 psia
Gasoline		✓	✓	Transported and stored as a liquid
Diesel		✓	✓	Transported and stored as a liquid
Methanol		✓	✓	Transported and stored as a liquid
Ethanol		✓	✓	Transported and stored as a liquid

[1] Off-board storage pressure depends on the fuel chain selection. Compressed hydrogen pipeline delivery and low pressure storage for use in MH FCVs will be around 150 psia. Compressed hydrogen tube trailer delivery and high pressure storage for use in cH_2 FCVs will be around 3600 psia.



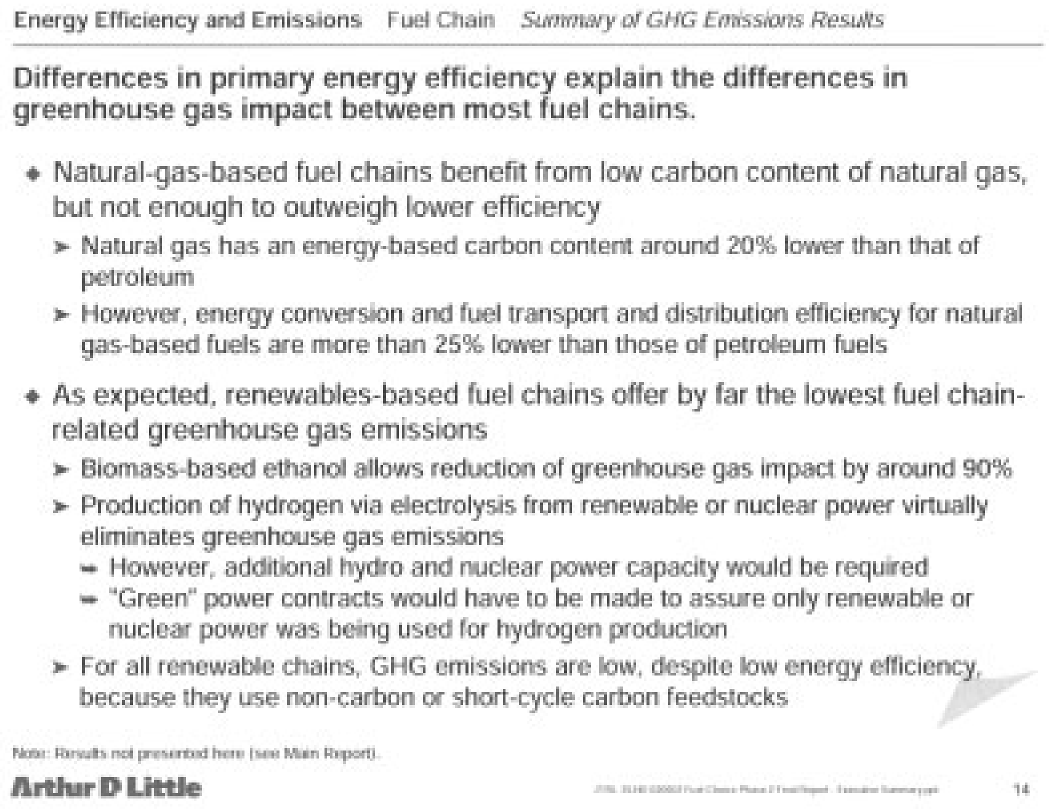
Background, Objectives, and Scope Scope *Caveats*

Not all issues potentially facing FCVs and hydrogen infrastructure were addressed in this study.

- Given the early stage of development of FCVs and hydrogen infrastructure, certain issues have yet to be resolved
  - Some technical challenges facing fuel cell systems and vehicle integration:
    - ZnO bed replacement (for sulfur removal)
    - impurities effects on catalysts (e.g. salt, sulfur, smoke)
    - startup time
    - freezing conditions
    - necessary on-board safety
    - transient control issues
  - Certain hydrogen infrastructure issues:
    - footprint and space constraints for on-site production and storage
    - varying land rental, labor, and permitting costs
    - access for hydrogen delivery options (e.g. tube trailer street access, right of way for pipelines)
- Although we identified these issues, we did not incorporate their potential cost or efficiency implications

The analysis results should be considered in conjunction with all the assumptions presented in the main report and appendix.

Arthur D Little 14



Energy Efficiency and Emissions Fuel Chain *Summary of GHG Emissions Results*

Differences in primary energy efficiency explain the differences in greenhouse gas impact between most fuel chains.

- Natural-gas-based fuel chains benefit from low carbon content of natural gas, but not enough to outweigh lower efficiency
  - Natural gas has an energy-based carbon content around 20% lower than that of petroleum
  - However, energy conversion and fuel transport and distribution efficiency for natural gas-based fuels are more than 25% lower than those of petroleum fuels
- As expected, renewables-based fuel chains offer by far the lowest fuel chain-related greenhouse gas emissions
  - Biomass-based ethanol allows reduction of greenhouse gas impact by around 90%
  - Production of hydrogen via electrolysis from renewable or nuclear power virtually eliminates greenhouse gas emissions
    - However, additional hydro and nuclear power capacity would be required
    - "Green" power contracts would have to be made to assure only renewable or nuclear power was being used for hydrogen production
  - For all renewable chains, GHG emissions are low, despite low energy efficiency, because they use non-carbon or short-cycle carbon feedstocks

Note: Results not presented here (see Main Report).

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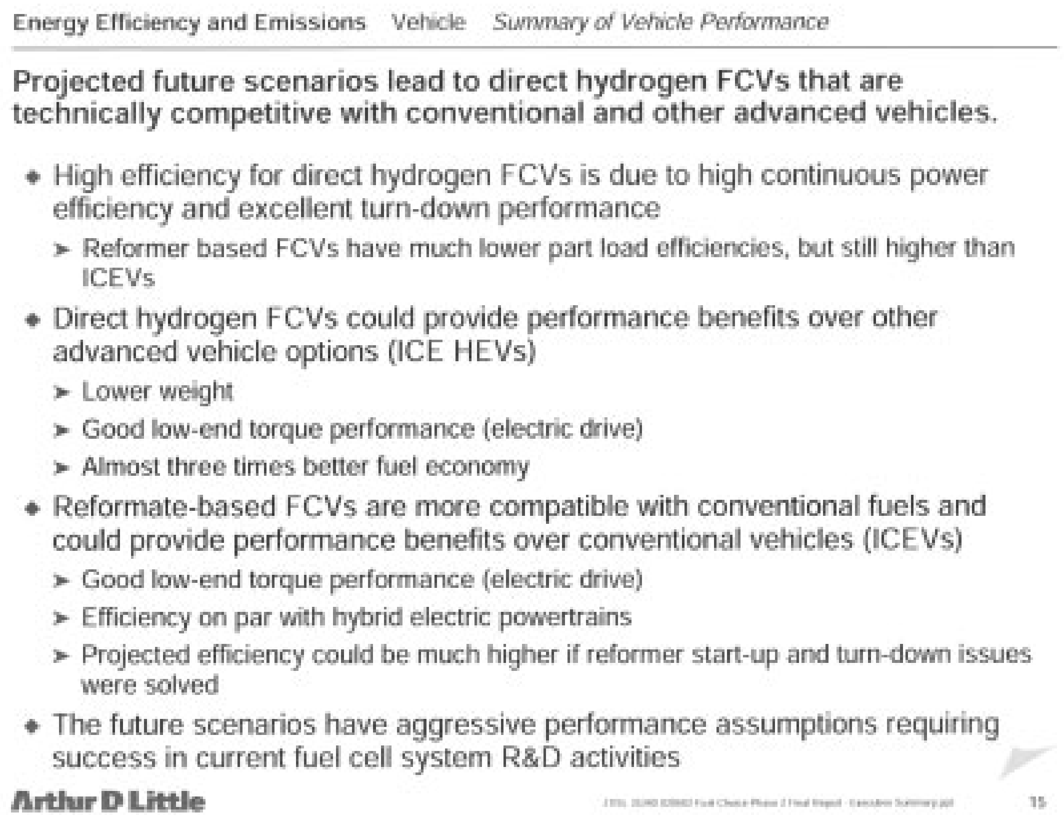
14



Projected future scenarios lead to direct hydrogen FCVs that are technically competitive with conventional and other advanced vehicles.

- High efficiency for direct hydrogen FCVs is due to high continuous power efficiency and excellent turn-down performance
  - Reformer based FCVs have much lower part load efficiencies, but still higher than ICEVs
- Direct hydrogen FCVs could provide performance benefits over other advanced vehicle options (ICE HEVs)
  - Lower weight
  - Good low-end torque performance (electric drive)
  - Almost three times better fuel economy
- Reformate-based FCVs are more compatible with conventional fuels and could provide performance benefits over conventional vehicles (ICEVs)
  - Good low-end torque performance (electric drive)
  - Efficiency on par with hybrid electric powertrains
  - Projected efficiency could be much higher if reformer start-up and turn-down issues were solved
- The future scenarios have aggressive performance assumptions requiring success in current fuel cell system R&D activities

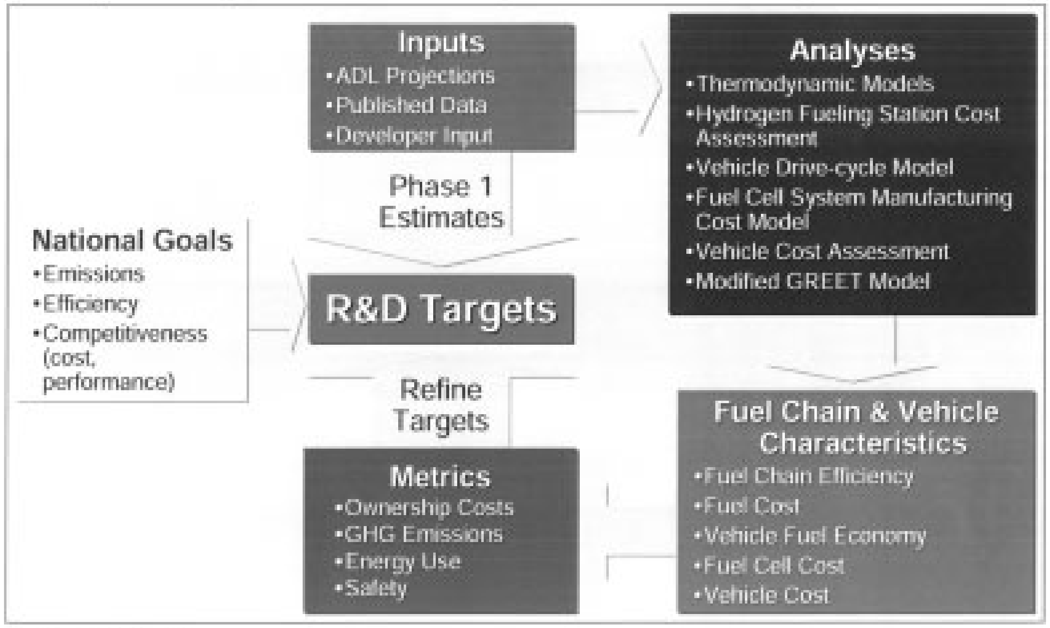
Arthur D Little

Outline

Main Report

- Background, Objectives & Scope
- **Approach**
- Energy Efficiency and Emissions
- Cost
- Safety
- Conclusion & DOE Target Setting

Combining a variety of inputs through thorough analyses, we are able to develop meaningful and defensible guidelines for R&D targets.



National Goals
- Emissions
- Efficiency
- Competitiveness (cost, performance)

Inputs
- ADL Projections
- Published Data
- Developer Input

Phase 1 Estimates

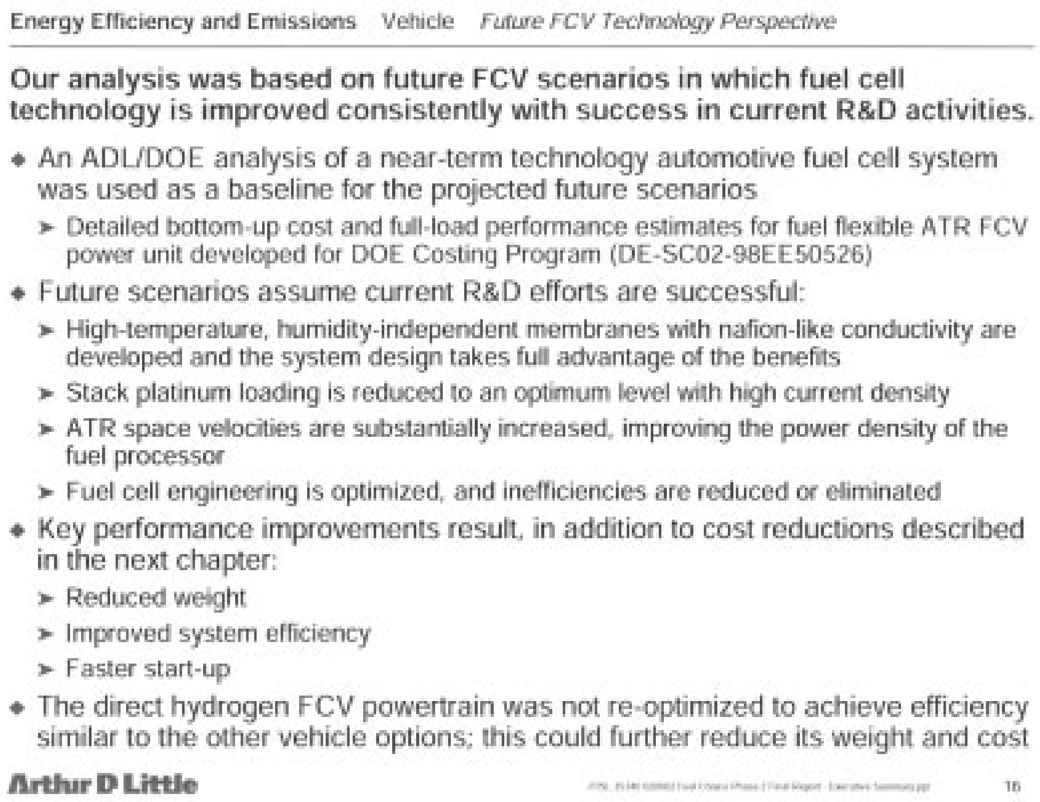
R&D Targets

Refine Targets

Metrics
- Ownership Costs
- GHG Emissions
- Energy Use
- Safety

Analyses
- Thermodynamic Models
- Hydrogen Fueling Station Cost Assessment
- Vehicle Drive-cycle Model
- Fuel Cell System Manufacturing Cost Model
- Vehicle Cost Assessment
- Modified GREET Model

Fuel Chain & Vehicle Characteristics
- Fuel Chain Efficiency
- Fuel Cost
- Vehicle Fuel Economy
- Fuel Cell Cost
- Vehicle Cost

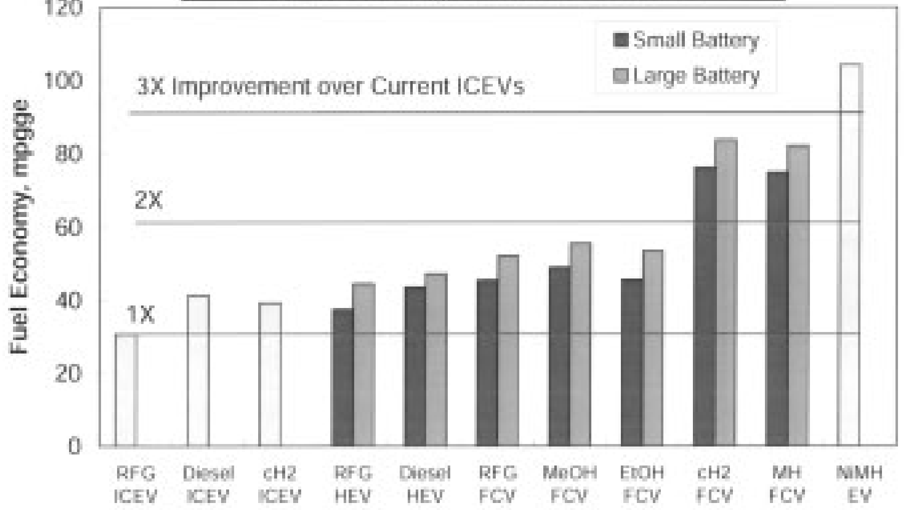


Our analysis was based on future FCV scenarios in which fuel cell technology is improved consistently with success in current R&D activities.

- An ADL/DOE analysis of a near-term technology automotive fuel cell system was used as a baseline for the projected future scenarios
    - ➤ Detailed bottom-up cost and full-load performance estimates for fuel flexible ATR FCV power unit developed for DOE Costing Program (DE-SC02-98EE50526)
- Future scenarios assume current R&D efforts are successful:
    - ➤ High-temperature, humidity-independent membranes with nafion-like conductivity are developed and the system design takes full advantage of the benefits
    - ➤ Stack platinum loading is reduced to an optimum level with high current density
    - ➤ ATR space velocities are substantially increased, improving the power density of the fuel processor
    - ➤ Fuel cell engineering is optimized, and inefficiencies are reduced or eliminated
- Key performance improvements result, in addition to cost reductions described in the next chapter:
    - ➤ Reduced weight
    - ➤ Improved system efficiency
    - ➤ Faster start-up
- The direct hydrogen FCV powertrain was not re-optimized to achieve efficiency similar to the other vehicle options; this could further reduce its weight and cost

Under the future scenarios, the direct hydrogen FCV gives more than 2.5 times better fuel economy than the conventional gasoline ICE vehicle.

Fuel Economy for Midsize Vehicles



The large battery cases give better fuel economy, due to greater regenerative braking, so we used it for the subsequent well-to-wheel analysis.

Approach Information Sources and Benefits to DOE

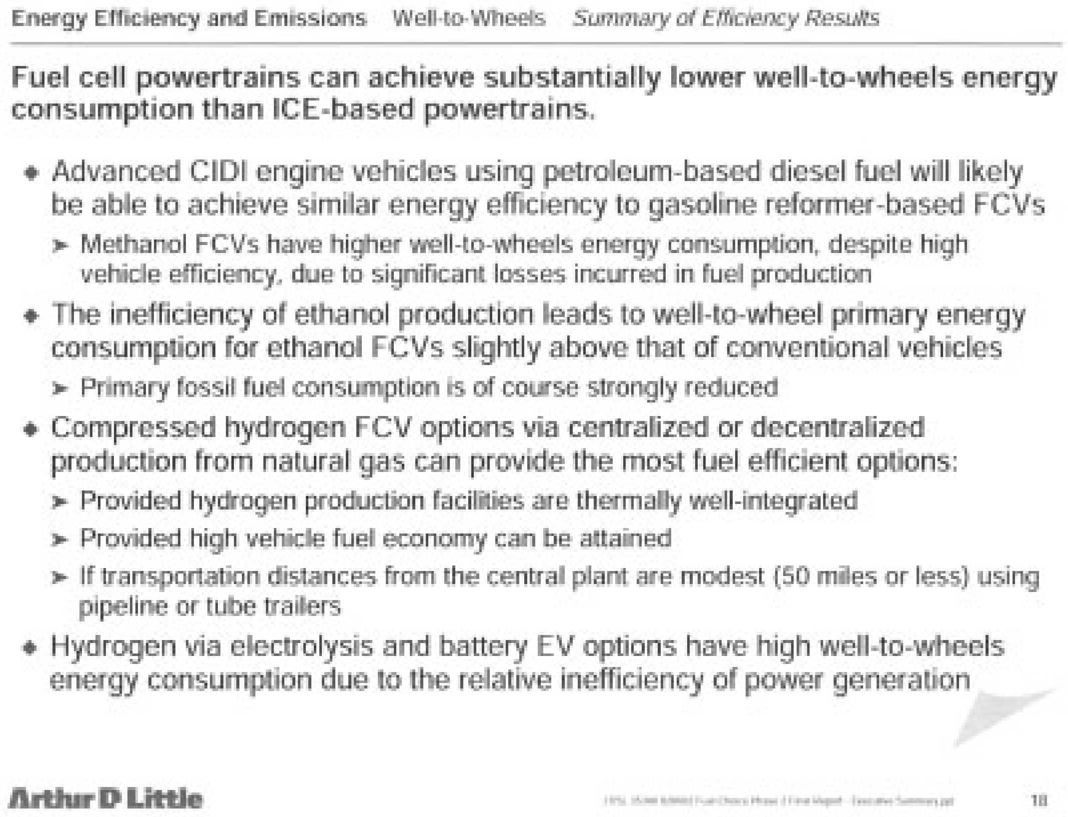
We used published and in-house data and information to develop a thorough analysis of FCV fuel options.

- Performed detailed well-to-wheel performance and cost calculations:
  - Built on existing models and analysis for energy efficiency and greenhouse gas emissions (specifically ADL in-house data and ANL's GREET model)
  - Added cost estimates for both fuel chain and vehicle consistent with on-going Arthur D. Little analyses for DOE
- Identified major potential safety issues with each fuel choice and characterized current industry efforts to address them
- Used the results to help DOE set targets that are aggressive but realistic
- The benefits of this analysis to DOE include:
  - Uses best available inputs for the fuel chain and vehicle analyses
  - Provides an independent analysis for DOE
  - Powertrain inputs to the vehicle analyses can be directly linked to our detailed cost and performance assessment of on-board reformer FCVs
  - Leverage DOE's investment in the GREET modeling spreadsheet and use its input assumptions where appropriate

We used Argonne National Laboratory's GREET model as a starting point for our analysis, refined it and added a cost assessment.

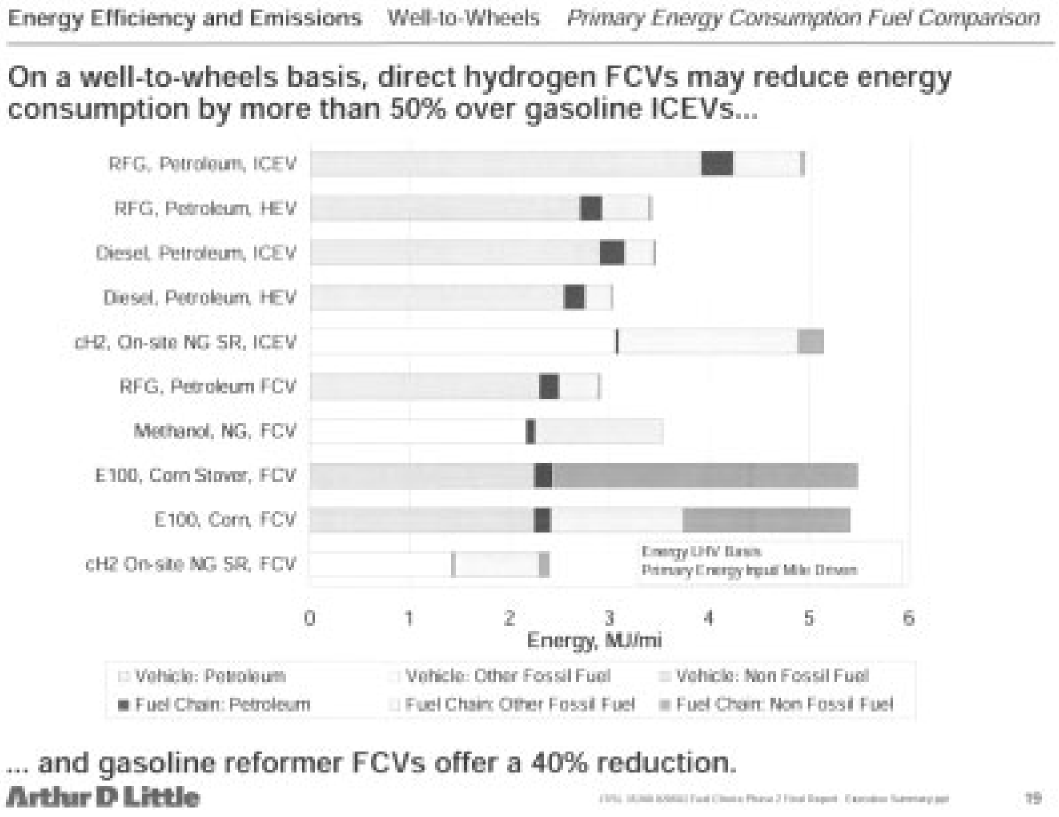
- Separated the well-to-tank analysis from the tank-to-wheel analysis to allow for transparent comparisons with conventional technology
- Updated the fuel chain assumptions with in-house ADL information and original analysis where necessary:
  - Refined hydrogen production and refueling options based on in-house analysis
  - Improved analysis for ethanol and methanol
- Incorporated a more detailed and thorough analysis of FCV performance:
  - Vehicle drive-cycle analysis for two different vehicle types (5-passenger sedan and SUV)
  - Careful assessment of fuel cell system turn-down characteristics
- Added cost models:
  - Fuel chain cost based on EIA projections and bottom-up calculations
  - Fuel cell power unit costs based on our detailed bottom-up cost estimates developed under a separate DOE program

This section provides an overview of the methodologies used; more detailed analyses are shown in the subsequent chapters.



Fuel cell powertrains can achieve substantially lower well-to-wheels energy consumption than ICE-based powertrains.

- Advanced CIDI engine vehicles using petroleum-based diesel fuel will likely be able to achieve similar energy efficiency to gasoline reformer-based FCVs
    - Methanol FCVs have higher well-to-wheels energy consumption, despite high vehicle efficiency, due to significant losses incurred in fuel production
- The inefficiency of ethanol production leads to well-to-wheel primary energy consumption for ethanol FCVs slightly above that of conventional vehicles
    - Primary fossil fuel consumption is of course strongly reduced
- Compressed hydrogen FCV options via centralized or decentralized production from natural gas can provide the most fuel efficient options:
    - Provided hydrogen production facilities are thermally well-integrated
    - Provided high vehicle fuel economy can be attained
    - If transportation distances from the central plant are modest (50 miles or less) using pipeline or tube trailers
- Hydrogen via electrolysis and battery EV options have high well-to-wheels energy consumption due to the relative inefficiency of power generation



Energy Efficiency and Emissions Well-to-Wheels *Primary Energy Consumption Fuel Comparison*

On a well-to-wheels basis, direct hydrogen FCVs may reduce energy consumption by more than 50% over gasoline ICEVs...

... and gasoline reformer FCVs offer a 40% reduction.

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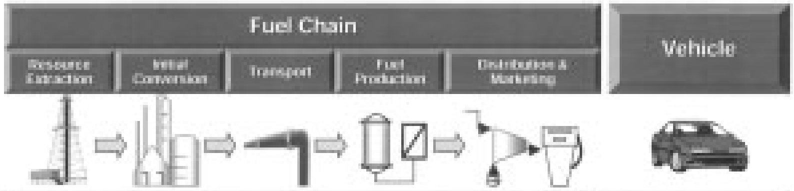
Details on pages: A5, 8-9

Approach   Fuel Chain / Vehicle Separation

We separated the well-to-tank analysis from the tank-to-wheel analysis to allow for easy comparisons with conventional technology.



Energy Efficiency	% or MJ primary energy input / MJ fuel delivered	$\text{mpg}_{\text{gasoline equivalent}}$
	$\text{MJ}_{\text{primary energy input}}/\text{mile}_{\text{driven}}$	
Greenhouse Gas Emissions	$g_{\text{GHG fuel chain}}$ / GJ fuel delivered	$g_{\text{GHG tailpipe}}/\text{mile}_{\text{driven}}$
	$g_{\text{GHG total}}/\text{mile}_{\text{driven}}$	
Cost	\$/GJ, or \$/gallon gasoline equivalent	\$/kW \$/vehicle
	\$/year	

Details on pages:
A10-13; AS 7-25

To analyze well-to-tank impacts, we separated each fuel chain into five modules.

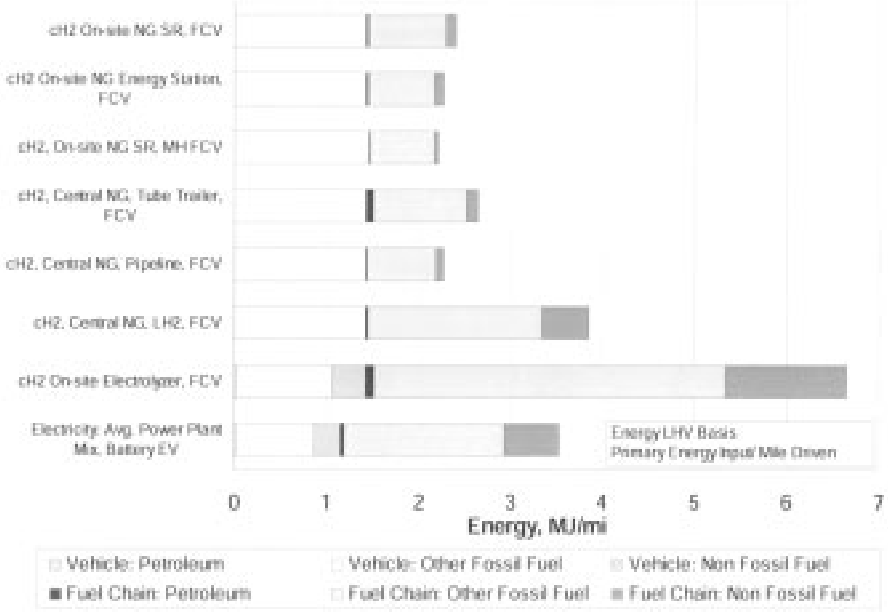
Energy Source	Step Energy Use (Input MJ/MJ Output), LHV basis				
	NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
Natural Gas	1.02	1.02	1.00[illegible]	1.36	---
Petroleum	0.013	---	---	---	---
Gasoline	0.045	---	---	---	---
Diesel	0.013	---	---	---	---
Electricity[1]	0.013	0.02	0.001	0.016	0.078
Hydrogen	---	---	---	---	1.03

* Not complete without all performance inputs and assumptions for each fuel chain.

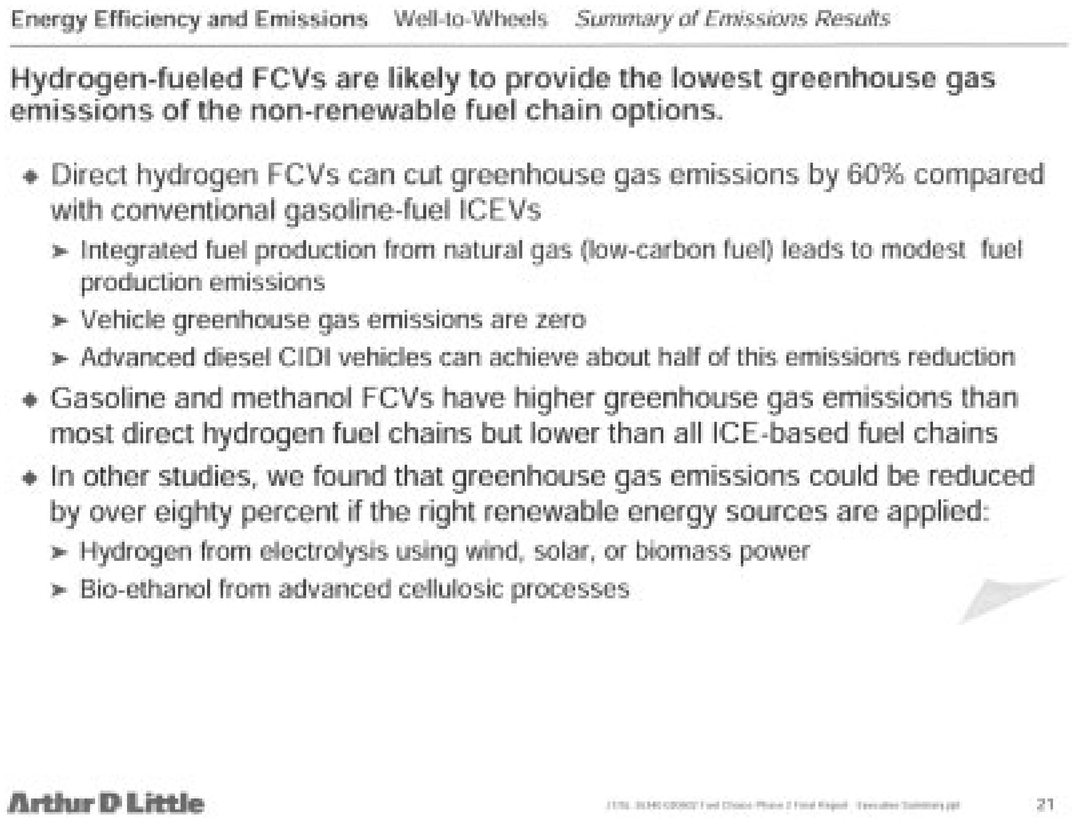
[1] Electricity is further broken down into primary fuel requirements based on the U.S. average power plant fuel mix.

We used GREET as a starting point, but performed separate analyses to refine performance and cost inputs when necessary.

Hydrogen via electrolysis and battery EV options have high energy consumption due to the relative inefficiency of power generation.



* Electrolyzer energy consumption assumes a US average mix of grid power.



Energy Efficiency and Emissions Well-to-Wheels *Summary of Emissions Results*

Hydrogen-fueled FCVs are likely to provide the lowest greenhouse gas emissions of the non-renewable fuel chain options.

- Direct hydrogen FCVs can cut greenhouse gas emissions by 60% compared with conventional gasoline-fuel ICEVs
  - Integrated fuel production from natural gas (low-carbon fuel) leads to modest fuel production emissions
  - Vehicle greenhouse gas emissions are zero
  - Advanced diesel CIDI vehicles can achieve about half of this emissions reduction
- Gasoline and methanol FCVs have higher greenhouse gas emissions than most direct hydrogen fuel chains but lower than all ICE-based fuel chains
- In other studies, we found that greenhouse gas emissions could be reduced by over eighty percent if the right renewable energy sources are applied:
  - Hydrogen from electrolysis using wind, solar, or biomass power
  - Bio-ethanol from advanced cellulosic processes

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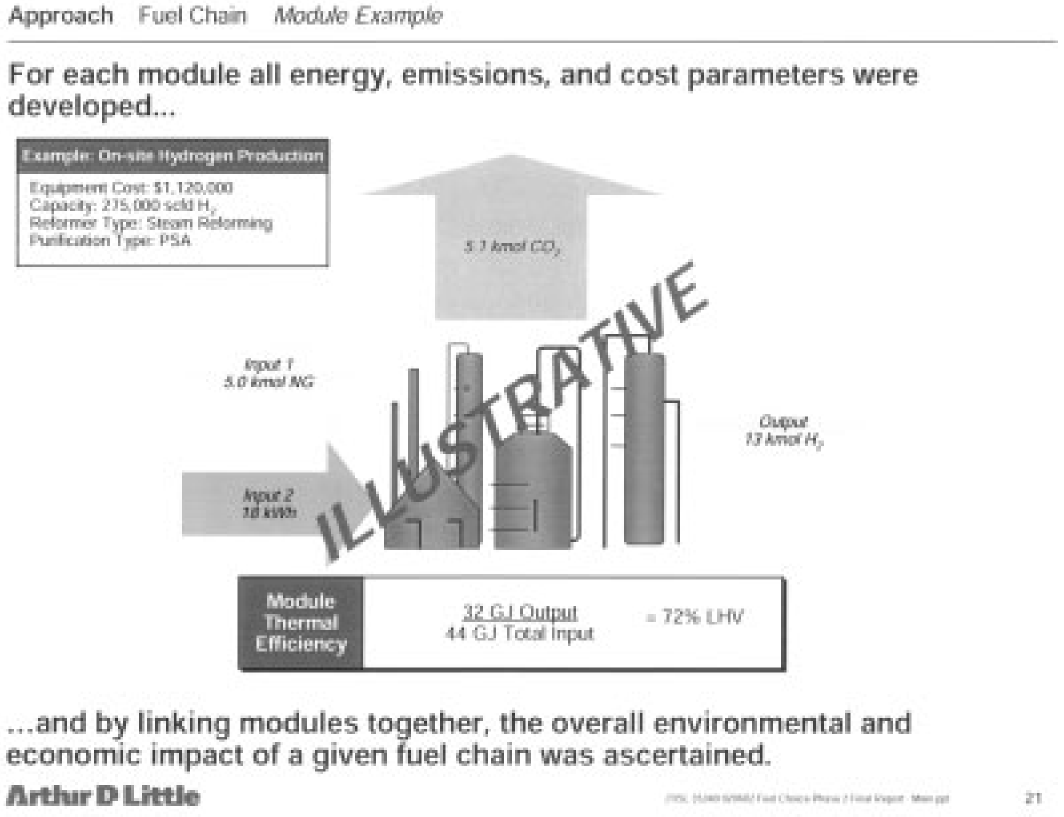
21



Approach Fuel Chain *Module Example*

For each module all energy, emissions, and cost parameters were developed...

Example: On-site Hydrogen Production

Equipment Cost: $1,120,000
Capacity: 275,000 scfd H_2
Reformer Type: Steam Reforming
Purification Type: PSA

Module Thermal Efficiency	$\frac{\text{32 GJ Output}}{\text{44 GJ Total Input}}$	= 72% LHV

...and by linking modules together, the overall environmental and economic impact of a given fuel chain was ascertained.

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Details on pages:
M34-35, 67-72;
A16-17

The hydrogen fuel chain analysis builds on a recent project for DOE's Hydrogen Program, where we have analyzed the cost and performance of local hydrogen fueling stations in detail.

- We included the three most relevant on-site production methods from an on-going study for DOE's Hydrogen Program (DE-FC36-00GO10604):
  - Steam reforming natural gas, PSA purification, and compressed hydrogen storage[1]
  - Electrolysis with compressed hydrogen storage[1]
  - Central production & distribution options were added in addition
- Original analysis was needed to update the performance and cost estimates for hydrogen fuel chains
  - Detailed thermodynamic analysis of on-site hydrogen production
  - Detailed design considerations for hydrogen storage & dispensing
  - Cost analysis based on vendor quotes, publications, and bottom-up analysis
  - Consistent (but not necessarily identical) assumptions for central hydrogen production facilities and on-site production
  - Consistent transport and distribution assumptions for hydrogen and other fuels
- The cost estimates are based on high production volumes (100 units/yr) to meet the mature market demand of direct hydrogen FCVs

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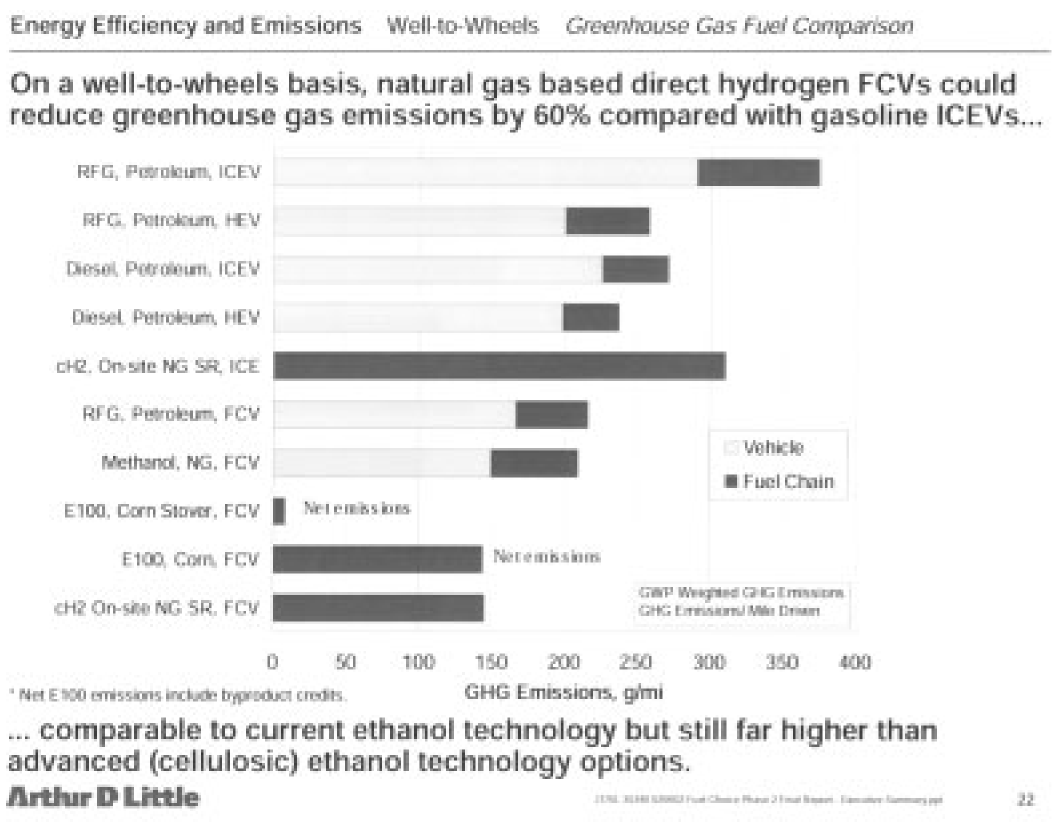
[1] High pressure on-site storage at 3600 psi with on-site boost compressors to achieve 5000 psi for cH_2 vehicles. Low pressure on-site storage at 100 psi for metal hydride vehicles.



Energy Efficiency and Emissions   Well-to-Wheels   *Greenhouse Gas Fuel Comparison*

On a well-to-wheels basis, natural gas based direct hydrogen FCVs could reduce greenhouse gas emissions by 60% compared with gasoline ICEVs...

* Net E100 emissions include byproduct credits.

... comparable to current ethanol technology but still far higher than advanced (cellulosic) ethanol technology options.

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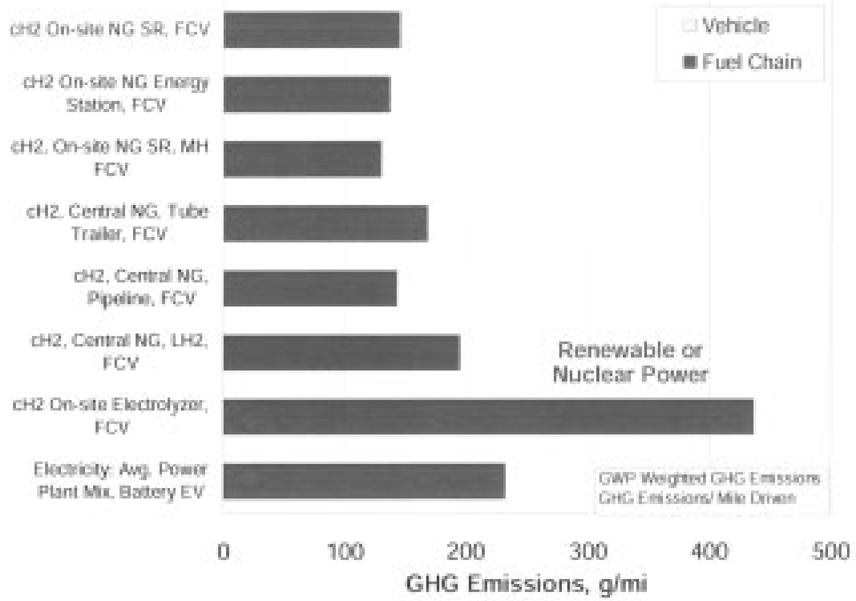
The lowest GHG emissions can be achieved by direct hydrogen vehicles using hydrogen made from renewable or nuclear power…



… even considerably lower than renewable ethanol.

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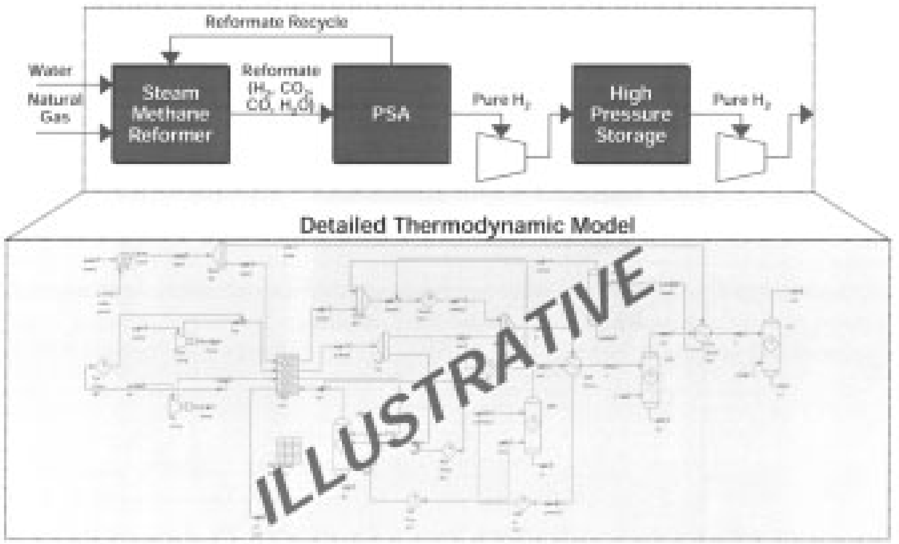
Thermodynamic modeling was used to characterize the performance of the on-site hydrogen production, purification, and compression modules.



Material and energy streams were integrated, and overall system efficiencies were determined for each case.

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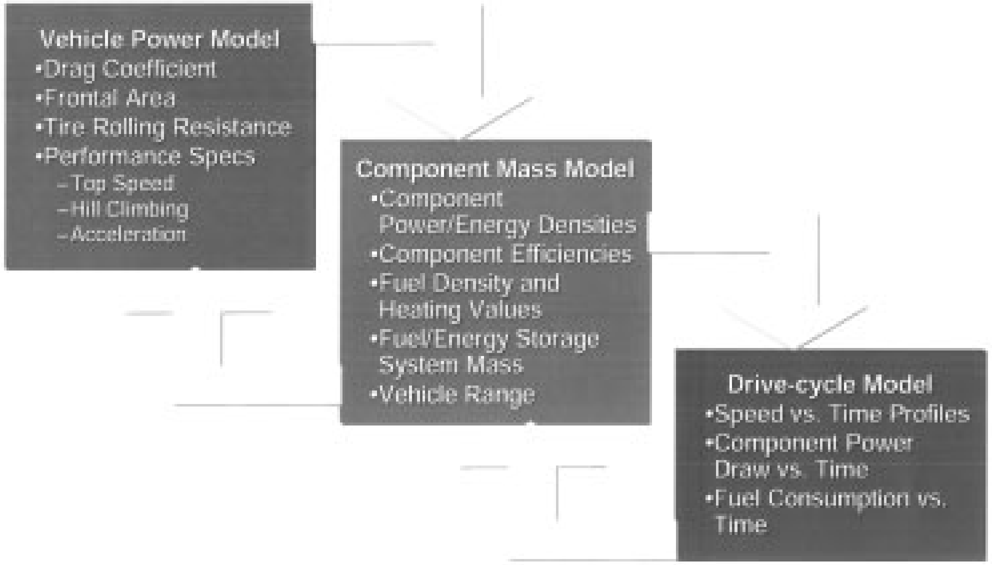
Details on pages:
A23-26

Approach Vehicle *Drive-cycle Analysis*

We used a simple vehicle drive-cycle simulation model to estimate fuel economy and power requirements for each powertrain.



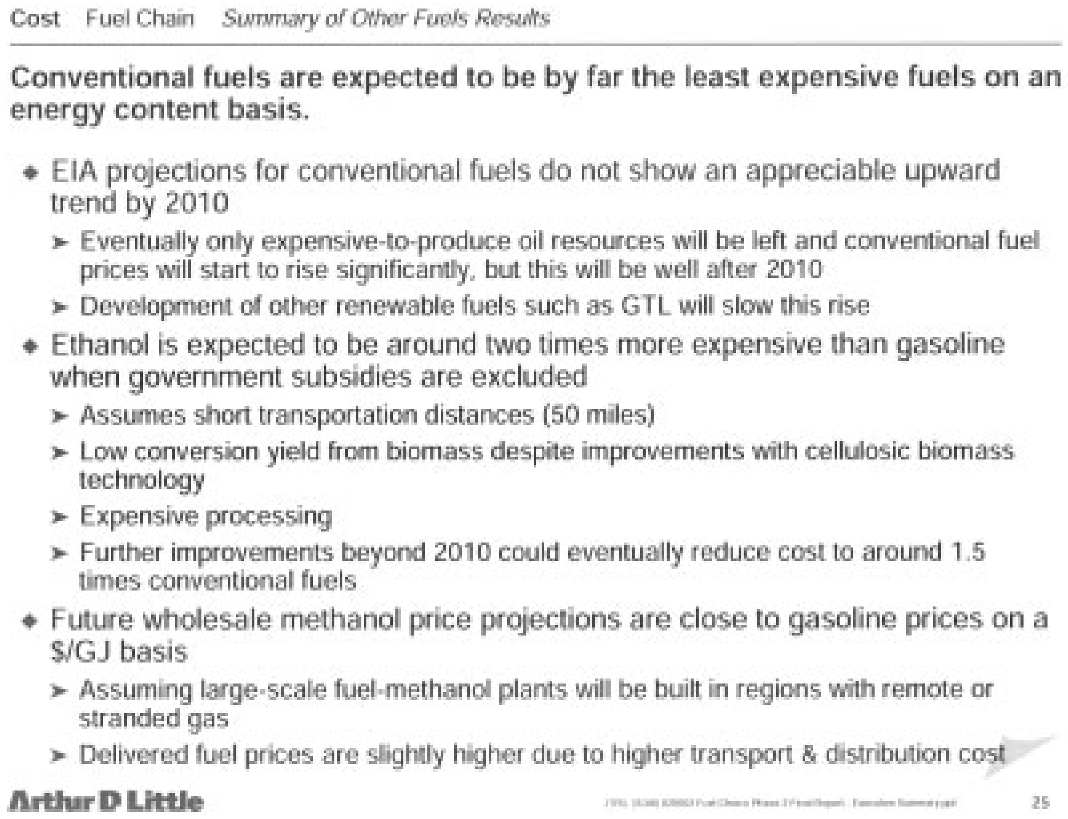
Vehicle Power Model
- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model
- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

Drive-cycle Model
- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

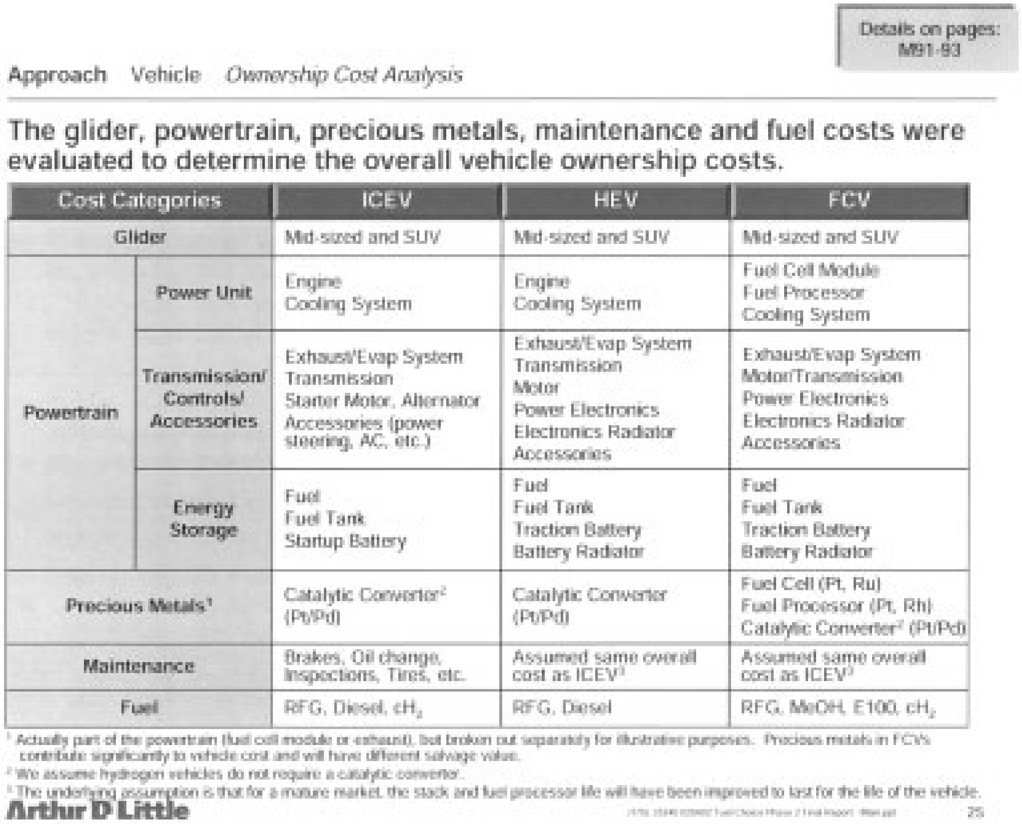
The most economical hydrogen fuel chains are expected to be over two times more expensive than gasoline, on a $/GJ basis.

- Capital costs are five to ten times more expensive than gasoline capital costs (including local and central plant capital)
    - Limitations in maximum train size (compared with refineries) and system complexity lead to high central plant capital cost
- Transportation and distribution costs (including compression and storage) are far higher than those for gasoline
- High feedstock cost dominates the high cost of locally produced hydrogen
- Electrolyzer-based production is costly with EIA energy price projections
    - Competitive with natural gas based reforming only if industrial electricity rates ($0.04/kWh) can be obtained at local fueling stations
    - When off-peak electric power is used, electrolysis equipment cost is higher because of low equipment utilization
- Alternative fuels, especially hydrogen, will require a significant upfront investment, representing a risk to both vehicle manufacture and fuel provider
    - Dealing with this risk represents a formidable barrier to the use of hydrogen for FCVs



Conventional fuels are expected to be by far the least expensive fuels on an energy content basis.

- EIA projections for conventional fuels do not show an appreciable upward trend by 2010
    - Eventually only expensive-to-produce oil resources will be left and conventional fuel prices will start to rise significantly, but this will be well after 2010
    - Development of other renewable fuels such as GTL will slow this rise
- Ethanol is expected to be around two times more expensive than gasoline when government subsidies are excluded
    - Assumes short transportation distances (50 miles)
    - Low conversion yield from biomass despite improvements with cellulosic biomass technology
    - Expensive processing
    - Further improvements beyond 2010 could eventually reduce cost to around 1.5 times conventional fuels
- Future wholesale methanol price projections are close to gasoline prices on a $/GJ basis
    - Assuming large-scale fuel-methanol plants will be built in regions with remote or stranded gas
    - Delivered fuel prices are slightly higher due to higher transport & distribution cost



Details on pages: M91-93

Approach Vehicle *Ownership Cost Analysis*

The glider, powertrain, precious metals, maintenance and fuel costs were evaluated to determine the overall vehicle ownership costs.

Cost Categories		ICEV	HEV	FCV
Glider		Mid-sized and SUV	Mid-sized and SUV	Mid-sized and SUV
Powertrain	Power Unit	Engine Cooling System	Engine Cooling System	Fuel Cell Module Fuel Processor Cooling System
	Transmission/ Controls/ Accessories	Exhaust/Evap System Transmission Starter Motor, Alternator Accessories (power steering, AC, etc.)	Exhaust/Evap System Transmission Motor Power Electronics Electronics Radiator Accessories	Exhaust/Evap System Motor/Transmission Power Electronics Electronics Radiator Accessories
	Energy Storage	Fuel Fuel Tank Startup Battery	Fuel Fuel Tank Traction Battery Battery Radiator	Fuel Fuel Tank Traction Battery Battery Radiator
Precious Metals[1]		Catalytic Converter[2] (Pt/Pd)	Catalytic Converter (Pt/Pd)	Fuel Cell (Pt, Ru) Fuel Processor (Pt, Rh) Catalytic Converter[2] (Pt/Pd)
Maintenance		Brakes, Oil change, Inspections, Tires, etc.	Assumed same overall cost as ICEV[3]	Assumed same overall cost as ICEV[3]
Fuel		RFG, Diesel, cH_2	RFG, Diesel	RFG, MeOH, E100, cH_2

[1] Actually part of the powertrain (fuel cell module or exhaust), but broken out separately for illustrative purposes. Precious metals in FCVs contribute significantly to vehicle cost and will have different salvage value.

[2] We assume hydrogen vehicles do not require a catalytic converter.

[3] The underlying assumption is that for a mature market, the stack and fuel processor life will have been improved to last for the life of the vehicle.

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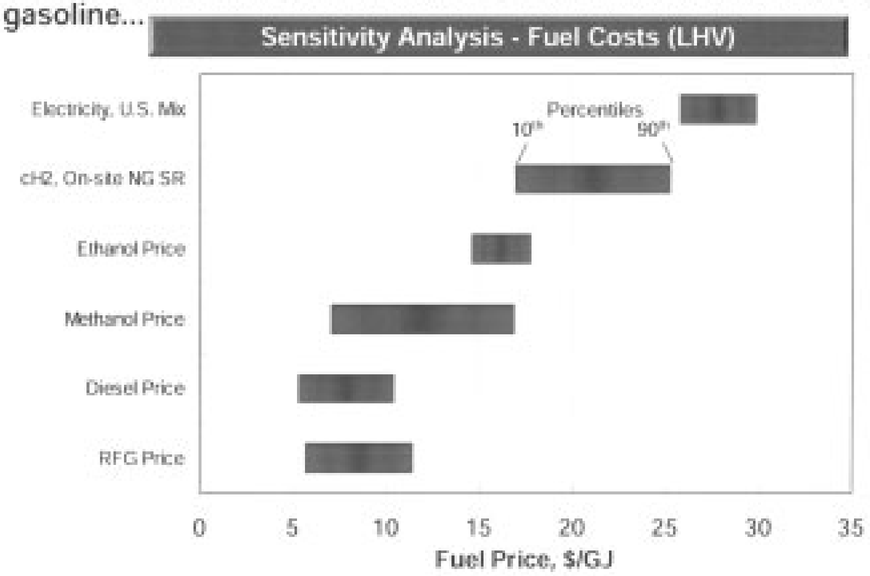
Details on pages:
M42-45, 84-86;
A56-61

Our FCV power unit analysis builds on ongoing ADL/DOE analysis of automotive fuel cell systems.

- In an ongoing program for DOE (DE-SCO2-98EE50526), ADL has developed a detailed cost and performance model for an on-board ATR FCV power unit
  - Model developed in conjunction with ANL, with feedback from OTT and PNGV
  - Assumes high production volumes but uses near-term performance inputs
- We have modified the model to estimate component costs and weights for scenarios of future performance
  - ADL, "Cost Analysis of Fuel Cell System for Transportation – Pathways to Low Cost", 2001 Final Report, prepared for DOE, to be published in 2002
  - High temperature membranes, increased power density, and improvements in fuel processor catalysts and other materials
  - These assumptions reflect a best-case scenario of success in current R&D activities, but do not project future technology leaps
- We have also developed future scenarios for for methanol, ethanol, and direct H_2 FCVs based on in-house kinetic and thermodynamic calculations
- The cost model estimates are based on high production volumes (500,000 units/yr) assuming mature manufacturing technology
  - These high volumes are not likely in the 2010 timeframe

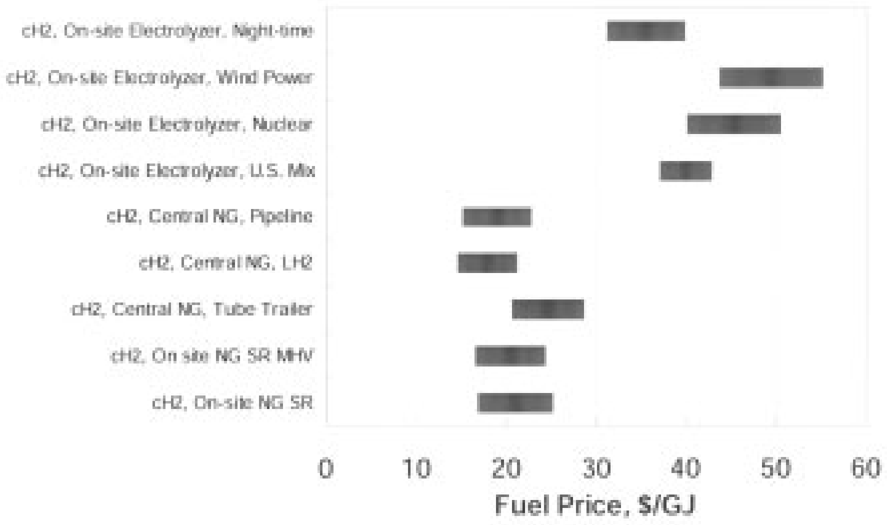
Even taking into account possible variations in fuel cost; electricity, hydrogen and ethanol are likely to be substantially more expensive than gasoline...



... while methanol may be competitive with gasoline and diesel in certain scenarios.

Uncertainty over electric power costs exacerbates the high cost of hydrogen from electrolyzers.

Sensitivity Analysis - Fuel Costs (LHV)



Details on pages:
M44, 84; A48-53

A previous ADL/EPRI HEV study provided the backbone for the overall vehicle factory cost analysis.

- ADL/EPRI study provided cost and weight estimates for HEV components
  - ➢ EPRI, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options", Palo Alto, June 2001
  - ➢ Reviewed component costs with ANL and GM
  - ➢ Glider, power unit, transmission/controls/accessories, and energy storage costs were determined for various vehicle requirements
- Fuel cell module, fuel processor, and precious metal estimates from the ADL/DOE study were combined with the EPRI study estimates to determine FCV cost and performance
  - ➢ We used the approach for determining hybrid vehicle costs and applied it to fuel cell powered vehicles
- We also made future assumptions for the hydrogen storage options considered in this analysis
  - ➢ High pressure compressed hydrogen storage in carbon fiber wrapped tanks
    - ➡ cost and performance based on claims by developers
  - ➢ Low pressure metal hydride storage
    - ➡ cost and performance based on internal analysis

Details on pages:
M96-108; A112-114

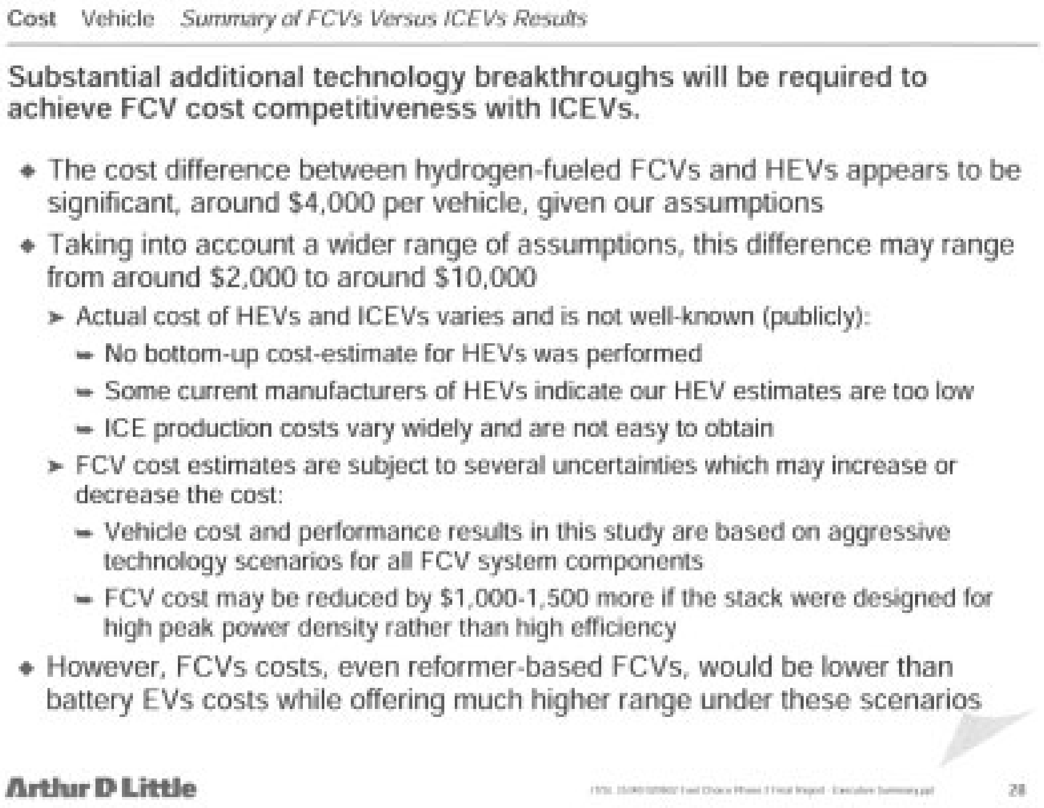
A safety analysis was necessary to identify the major safety concerns of the alternative fuel choices.

Scope

- Identify major safety concerns of fuel choices
- Perform safety issues analysis & identify ongoing efforts to resolve issues

Approach

- Review latest information on codes and standards
- Identify properties of each fuel that affects safety
- Focus on local storage, transportation, and end use in vehicles
  - All fuels are already produced for industrial applications
  - Use in light duty vehicle setting is new for many fuels
  - Include impact on building safety
- Identify key safety barriers for each fuel



Substantial additional technology breakthroughs will be required to achieve FCV cost competitiveness with ICEVs.

- The cost difference between hydrogen-fueled FCVs and HEVs appears to be significant, around $4,000 per vehicle, given our assumptions
- Taking into account a wider range of assumptions, this difference may range from around $2,000 to around $10,000
  - Actual cost of HEVs and ICEVs varies and is not well-known (publicly):
    - No bottom-up cost-estimate for HEVs was performed
    - Some current manufacturers of HEVs indicate our HEV estimates are too low
    - ICE production costs vary widely and are not easy to obtain
  - FCV cost estimates are subject to several uncertainties which may increase or decrease the cost:
    - Vehicle cost and performance results in this study are based on aggressive technology scenarios for all FCV system components
    - FCV cost may be reduced by $1,000-1,500 more if the stack were designed for high peak power density rather than high efficiency
- However, FCVs costs, even reformer-based FCVs, would be lower than battery EVs costs while offering much higher range under these scenarios

The cost and performance of the fuel cell stack remains the key barrier in achieving cost parity with HEVs or conventional vehicles.

- The additional cost being projected for FCVs over conventional and HEV platforms is clearly significant
  - Current FCV power unit cost is 2-3 times the DOE/PNGV target of $45/kW
  - System components not counted in the $45/kW target further increase difference in cost with ICEVs
  - By using different assumptions, the gap could be reduced but would remain significant
- The differences in cost between various FCV fuel choices is significant, but does not appear deciding compared to the difference with ICEVs
- Stack remains key to further improving the cost of FCVs
  - Stack cost by itself remains the largest FCV power unit component
  - Power density, CO tolerance, and other performance limitations determine the need for other subsystems
- However, in order to further reduce FCV cost, the cost of other subsystems and components will also need to be addressed
  - Future scenarios for motor and power electronics costs are nearly as expensive as the fuel cell stack

Details on pages:
M99-101; A104-111

Six major safety variables were evaluated for each fuel based on it's properties.

Fuel Properties

- Minimum Ignition Energy
- Flammability Limit
- Diffusion Coefficient
- Odor, Color
- Flame Visibility
- Storage Condition
- Vapor Density
- Vapor Pressure
- Energy Content (weight and volume)

Safety Variables

- Flammability and Detonation
- Ignition Energy
- Gas and Flame Detection
- Toxicity
- High Pressure Storage
- Cryogenic Storage

Evaluation of hydrogen safety issues is presented in the main report, other fuels' safety issue evaluations are in the Appendix.

Outline

Main Report

- Background, Objectives & Scope
- Approach
- **Energy Efficiency and Emissions**
- Cost
- Safety
- Conclusion & DOE Target Setting

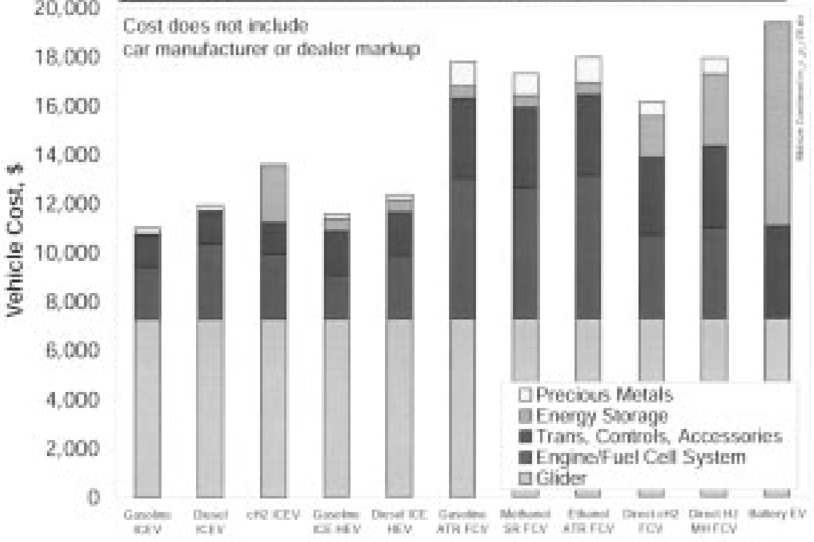
Powertrain costs for compressed-hydrogen FCVs would be significantly lower than those of systems with on-board reformers in our scenarios.

- Fuel processor-based FCVs are projected to cost $1,000-$2,000 more than compressed cH_2 vehicles:
  - Fuel processors add cost directly
  - Fuel processors add weight, which increases power requirements to achieve desired performance, thus adding to entire power unit cost
  - Reformers impact the performance of the fuel cell stack, and cause its cost to increase:
    - Due to poorer fuel quality of reformate (compared with pure hydrogen), including dilution and poisoning effects (CO and S), reformer-based fuel cell stacks must be larger or have higher platinum loadings
    - The reformer losses significantly impact the well-to-wheel efficiency; if direct hydrogen FCVs were optimized to achieve the same efficiency, their cost could be reduced further (this was not done for this study)
- Fuel processor-based FCVs would cost roughly the same as metal hydride-based FCVs

Nevertheless, the difference in cost does not appear decisive by itself in light of the difference in cost between all FCVs and HEVS and ICEVs.

Based on our scenario analysis, factory costs of future FCVs would likely be 40-60% higher than conventional vehicles, but lower than battery EVs.

Factory Costs for Small Battery Mid-sized Vehicles



Cost does not include car manufacturer or dealer markup

Note: All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

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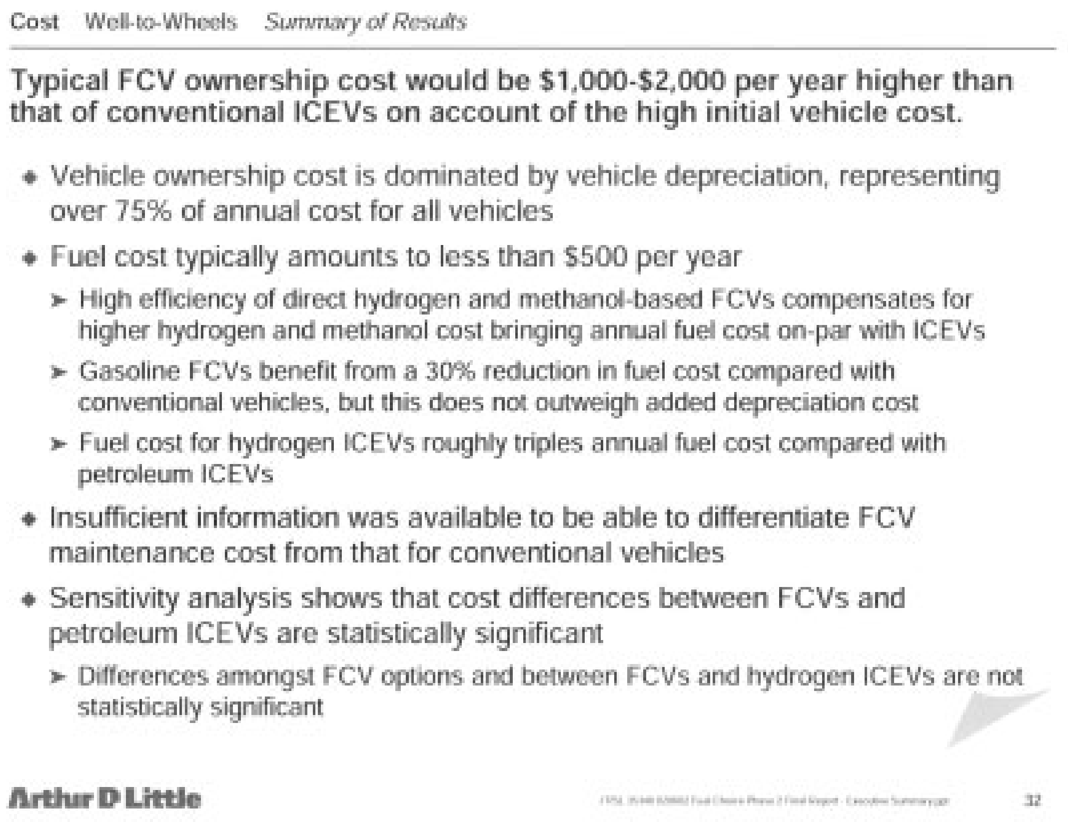
Outline

Main Report

- Background, Objectives & Scope
- Approach
- **Energy Efficiency and Emissions**
  - **Fuel Chain**
  - Vehicle
  - Well-to-Wheels
- C
- Safety
- Conclusion & DOE Target Setting

None of the alternative fuels can be delivered with greater primary energy conversion efficiency than conventional fuels.

- The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel
  - ➢ Oil refineries provide unparalleled primary fuel conversion efficiencies of ~85%
  - ➢ Syngas production from natural gas (as needed in the production of hydrogen and methanol) imposes an additional penalty of roughly 15% on these fuel chains
  - ➢ Extensive use of electric power penalizes energy efficiency even more significantly, making electrolysis chains over 3 times more energy intensive than hydrogen from on-site NG reformers, and almost 4 times more than gasoline
- Biomass-based conversion chains (ethanol) have fuel chain efficiencies below 50%, though much of this primary energy may be renewable
- Due to their high energy density, the primary energy use for transport and distribution of conventional fuels is the lowest
  - ➢ Transport and distribution comprise less than 5% of energy use for petroleum fuels
  - ➢ Alcohol fuels have roughly half the energy density of hydrocarbon fuels, and hence transportation energy use is roughly double that of conventional fuels
  - ➢ Energy use for the compression, liquefaction, or hydrate formation associated with hydrogen transport & vehicle storage adds 10-30% to primary energy use



Cost Well-to-Wheels *Summary of Results*

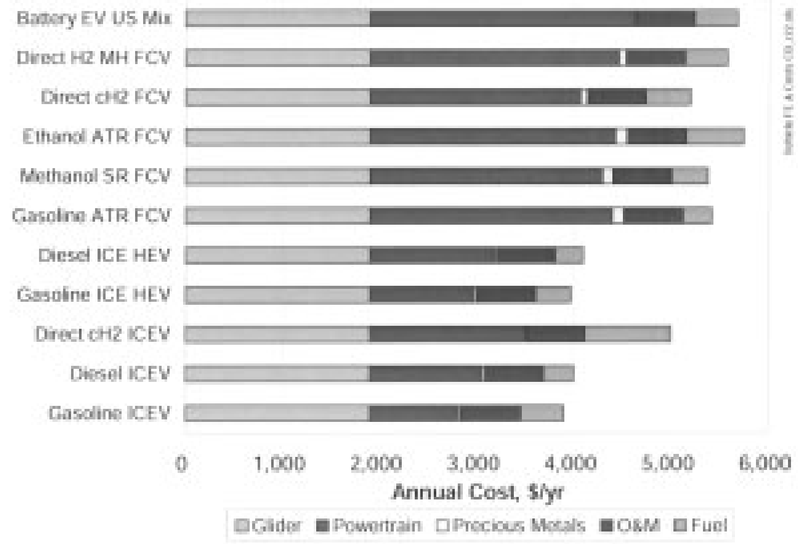
Typical FCV ownership cost would be $1,000-$2,000 per year higher than that of conventional ICEVs on account of the high initial vehicle cost.

- Vehicle ownership cost is dominated by vehicle depreciation, representing over 75% of annual cost for all vehicles
- Fuel cost typically amounts to less than $500 per year
  - High efficiency of direct hydrogen and methanol-based FCVs compensates for higher hydrogen and methanol cost bringing annual fuel cost on-par with ICEVs
  - Gasoline FCVs benefit from a 30% reduction in fuel cost compared with conventional vehicles, but this does not outweigh added depreciation cost
  - Fuel cost for hydrogen ICEVs roughly triples annual fuel cost compared with petroleum ICEVs
- Insufficient information was available to be able to differentiate FCV maintenance cost from that for conventional vehicles
- Sensitivity analysis shows that cost differences between FCVs and petroleum ICEVs are statistically significant
  - Differences amongst FCV options and between FCVs and hydrogen ICEVs are not statistically significant

Cost Well-to-Wheels *Mid-sized Vehicle Ownership Costs - Small Battery*

Typical annual mid-size FCV costs are projected to be around $1,200 to $1,800 more than that of conventional vehicles.

Vehicle Ownership Costs for Small Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

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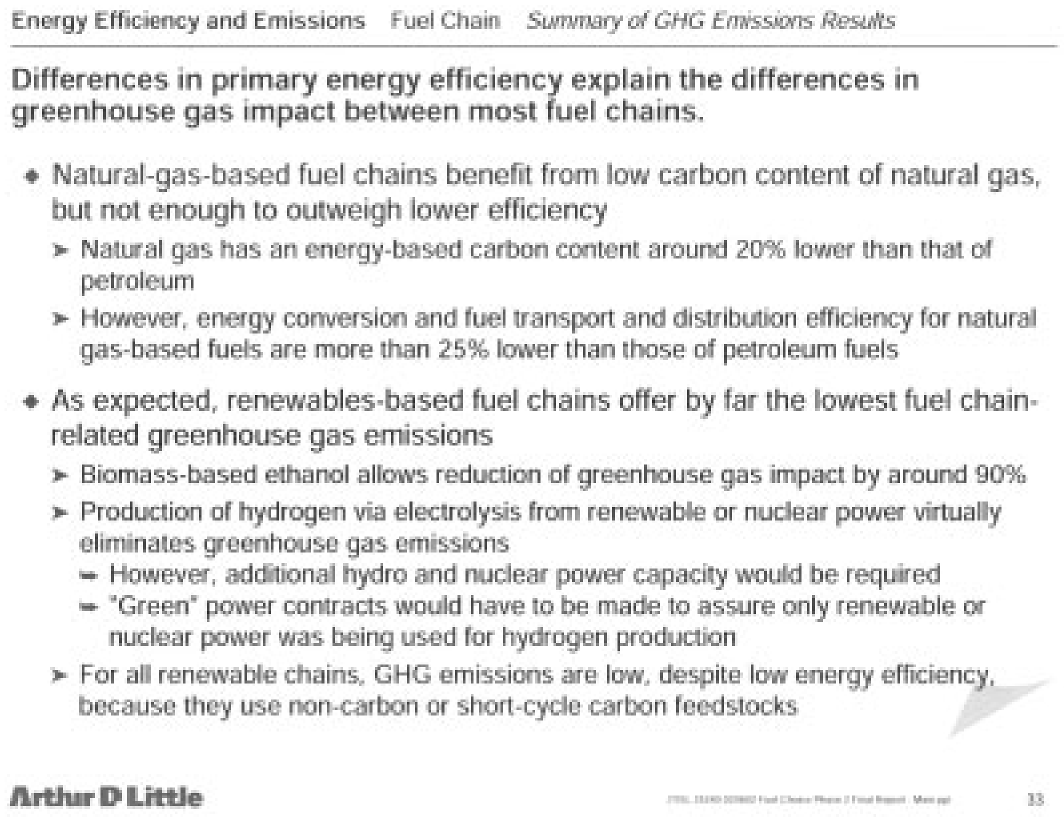

Energy Efficiency and Emissions Fuel Chain *Summary of GHG Emissions Results*

Differences in primary energy efficiency explain the differences in greenhouse gas impact between most fuel chains.

- Natural-gas-based fuel chains benefit from low carbon content of natural gas, but not enough to outweigh lower efficiency
  - Natural gas has an energy-based carbon content around 20% lower than that of petroleum
  - However, energy conversion and fuel transport and distribution efficiency for natural gas-based fuels are more than 25% lower than those of petroleum fuels
- As expected, renewables-based fuel chains offer by far the lowest fuel chain-related greenhouse gas emissions
  - Biomass-based ethanol allows reduction of greenhouse gas impact by around 90%
  - Production of hydrogen via electrolysis from renewable or nuclear power virtually eliminates greenhouse gas emissions
    - However, additional hydro and nuclear power capacity would be required
    - "Green" power contracts would have to be made to assure only renewable or nuclear power was being used for hydrogen production
  - For all renewable chains, GHG emissions are low, despite low energy efficiency, because they use non-carbon or short-cycle carbon feedstocks

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33

Details on pages:
A7, 19-20; AS27-62

Energy consumption for on-site hydrogen production was estimated with the use of thermodynamic models and discussions with (future) vendors.

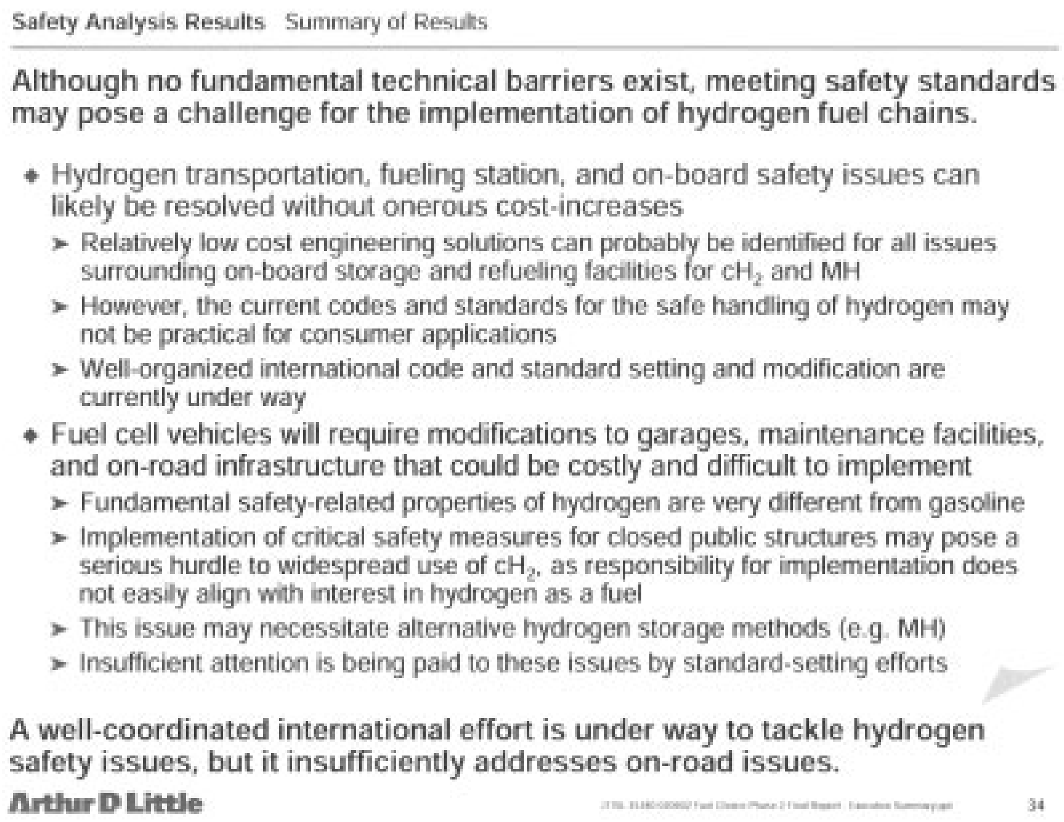
Local Hydrogen Fueling Station Energy Requirements (LHV) per kg Hydrogen			
Hydrogen Option	Natural Gas MMBtu/kg	Power kWh/kg	Total Primary Energy[4] (GJ/kg)
High pressure gas dispensing from Tube Trailer delivery[1]	-	1.25	0.013
High pressure gas dispensing from Liquid Hydrogen delivery[1]	-	0.05	0.001
High pressure gas dispensing from Pipeline delivery[2]	-	3.04	0.031
On-site Electrolyzer with high pressure gas dispensing[1]	-	50.0	0.500
On-site SR with high pressure gas dispensing[1]	0.150	3.37	0.192
On-site SR with low pressure gas dispensing for MH FCV[3]	0.150	1.34	0.172

[1] Maximum 3,600 psia (240 atm) local on-site storage to 5,000 psia (340 atm) on-board storage for cH_2 vehicles.

[2] Compression from 100 psia (8 atm) delivery pressure to 5,000 psia (340 atm) on-board storage for cH_2 vehicles. Some pipeline pressures can be as high as 740 psia (50 atm), requiring less local fueling station compression power.

[3] Maximum 130 psia (9 atm) local on-site storage to 130 psia (9 atm) on-board metal hydride storage for MH vehicles. Note: on-site storage pressure is below 130 psia when tanks are not full.

[4] Primary energy delivered to the fuel production facility. 1.055 GJ/MMBtu natural gas, electric power is represented as 0.01 GJ/kWh, assuming a 36% power plant efficiency.



Safety Analysis Results Summary of Results

Although no fundamental technical barriers exist, meeting safety standards may pose a challenge for the implementation of hydrogen fuel chains.

- Hydrogen transportation, fueling station, and on-board safety issues can likely be resolved without onerous cost-increases
  - Relatively low cost engineering solutions can probably be identified for all issues surrounding on-board storage and refueling facilities for cH_2 and MH
  - However, the current codes and standards for the safe handling of hydrogen may not be practical for consumer applications
  - Well-organized international code and standard setting and modification are currently under way
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and on-road infrastructure that could be costly and difficult to implement
  - Fundamental safety-related properties of hydrogen are very different from gasoline
  - Implementation of critical safety measures for closed public structures may pose a serious hurdle to widespread use of cH_2, as responsibility for implementation does not easily align with interest in hydrogen as a fuel
  - This issue may necessitate alternative hydrogen storage methods (e.g. MH)
  - Insufficient attention is being paid to these issues by standard-setting efforts

A well-coordinated international effort is under way to tackle hydrogen safety issues, but it insufficiently addresses on-road issues.

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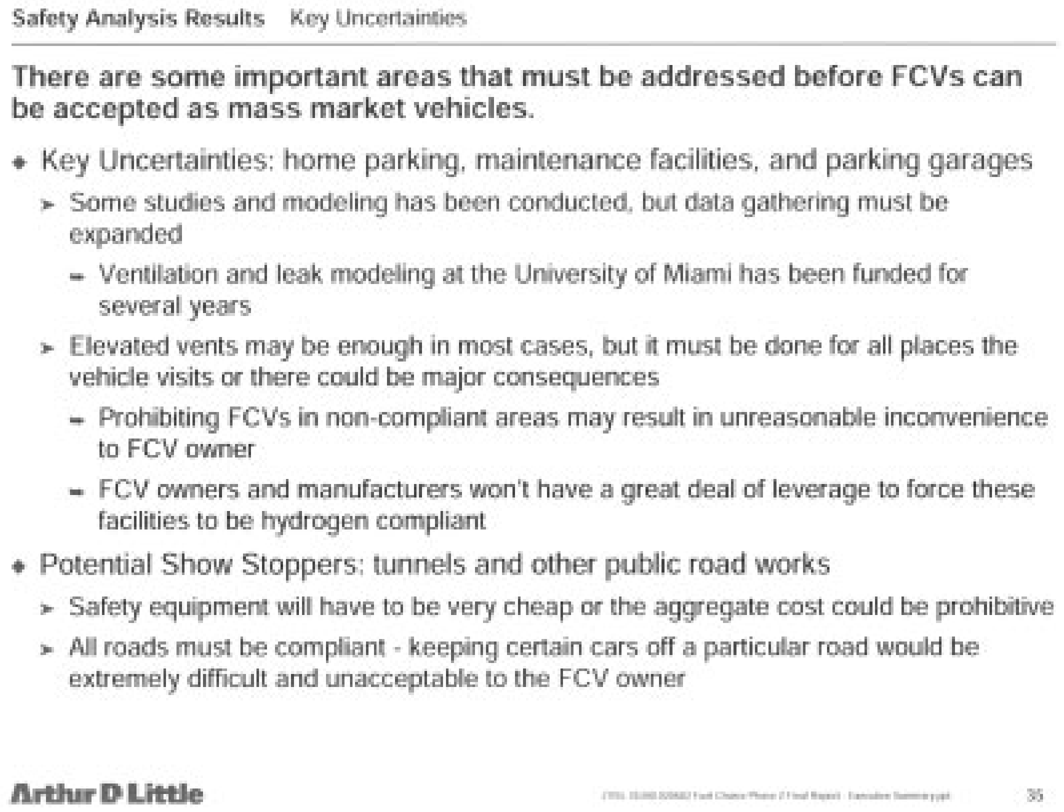
34



Safety Analysis Results Key Uncertainties

There are some important areas that must be addressed before FCVs can be accepted as mass market vehicles.

- Key Uncertainties: home parking, maintenance facilities, and parking garages
  - Some studies and modeling has been conducted, but data gathering must be expanded
    - Ventilation and leak modeling at the University of Miami has been funded for several years
  - Elevated vents may be enough in most cases, but it must be done for all places the vehicle visits or there could be major consequences
    - Prohibiting FCVs in non-compliant areas may result in unreasonable inconvenience to FCV owner
    - FCV owners and manufacturers won't have a great deal of leverage to force these facilities to be hydrogen compliant
- Potential Show Stoppers: tunnels and other public road works
  - Safety equipment will have to be very cheap or the aggregate cost could be prohibitive
  - All roads must be compliant - keeping certain cars off a particular road would be extremely difficult and unacceptable to the FCV owner

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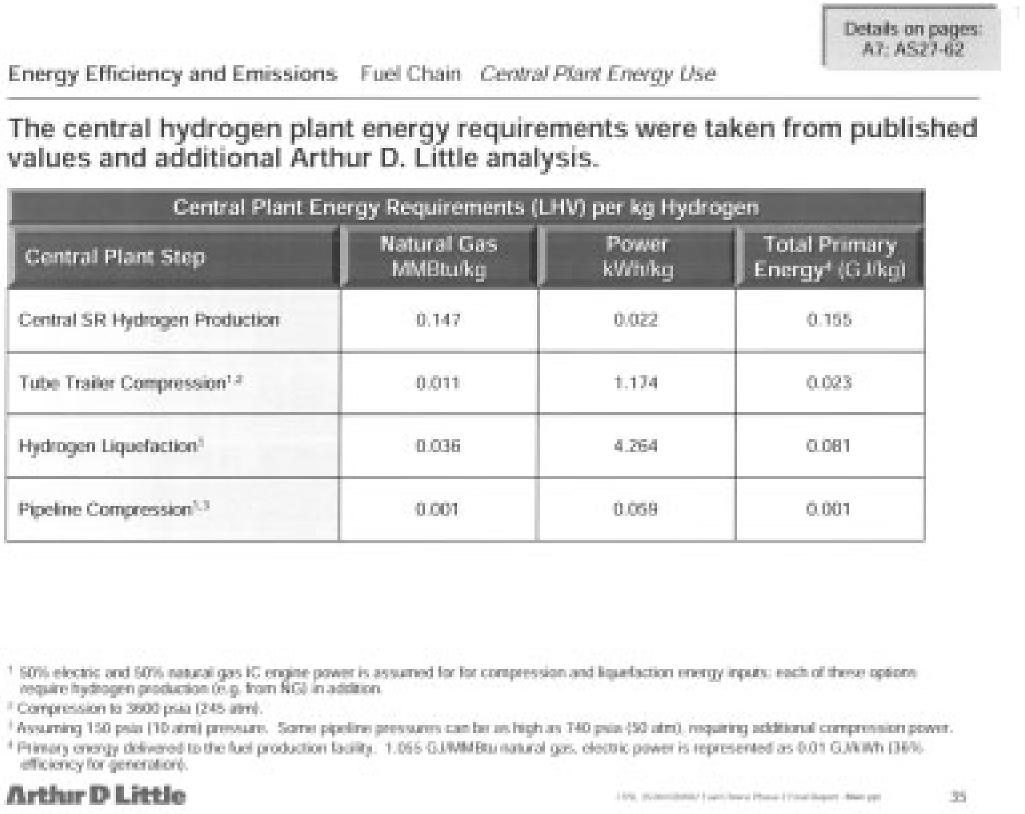
35



Details on pages:
A7; AS27-62

Energy Efficiency and Emissions   Fuel Chain   *Central Plant Energy Use*

The central hydrogen plant energy requirements were taken from published values and additional Arthur D. Little analysis.

Central Plant Energy Requirements (LHV) per kg Hydrogen			
Central Plant Step	Natural Gas MMBtu/kg	Power kWh/kg	Total Primary Energy[4] (GJ/kg)
Central SR Hydrogen Production	0.147	0.022	0.155
Tube Trailer Compression[1,2]	0.011	1.174	0.023
Hydrogen Liquefaction[1]	0.036	4.264	0.081
Pipeline Compression[1,3]	0.001	0.059	0.001

[1] 50% electric and 50% natural gas IC engine power is assumed for for compression and liquefaction energy inputs; each of these options require hydrogen production (e.g. from NG) in addition.

[2] Compression to 3600 psia (245 atm).

[3] Assuming 150 psia (10 atm) pressure. Some pipeline pressures can be as high as 740 psia (50 atm), requiring additional compression power.

[4] Primary energy delivered to the fuel production facility. 1.055 GJ/MMBtu natural gas, electric power is represented as 0.01 GJ/kWh (36% efficiency for generation).

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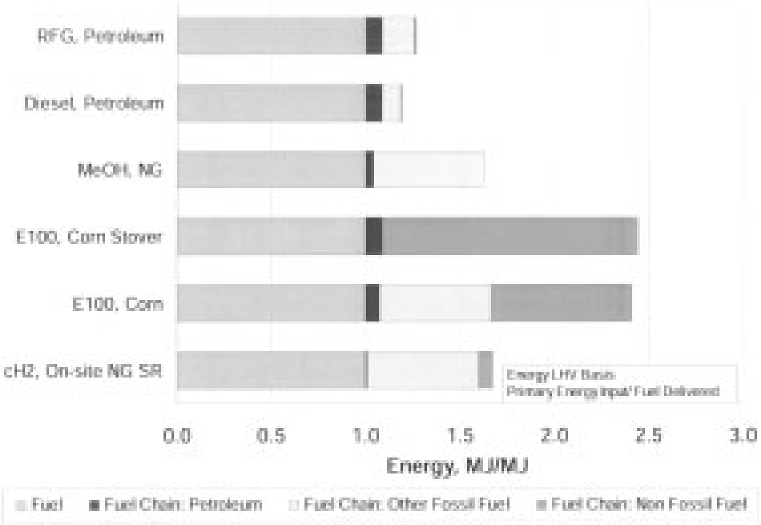
Details on pages:
M11, 18-21; A7,
19-20

Energy Efficiency and Emissions Fuel Chain *Well-Tank Energy Use Fuel Comparison*

The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel



* Net E100 energy use include byproduct credits, as do petroleum products.

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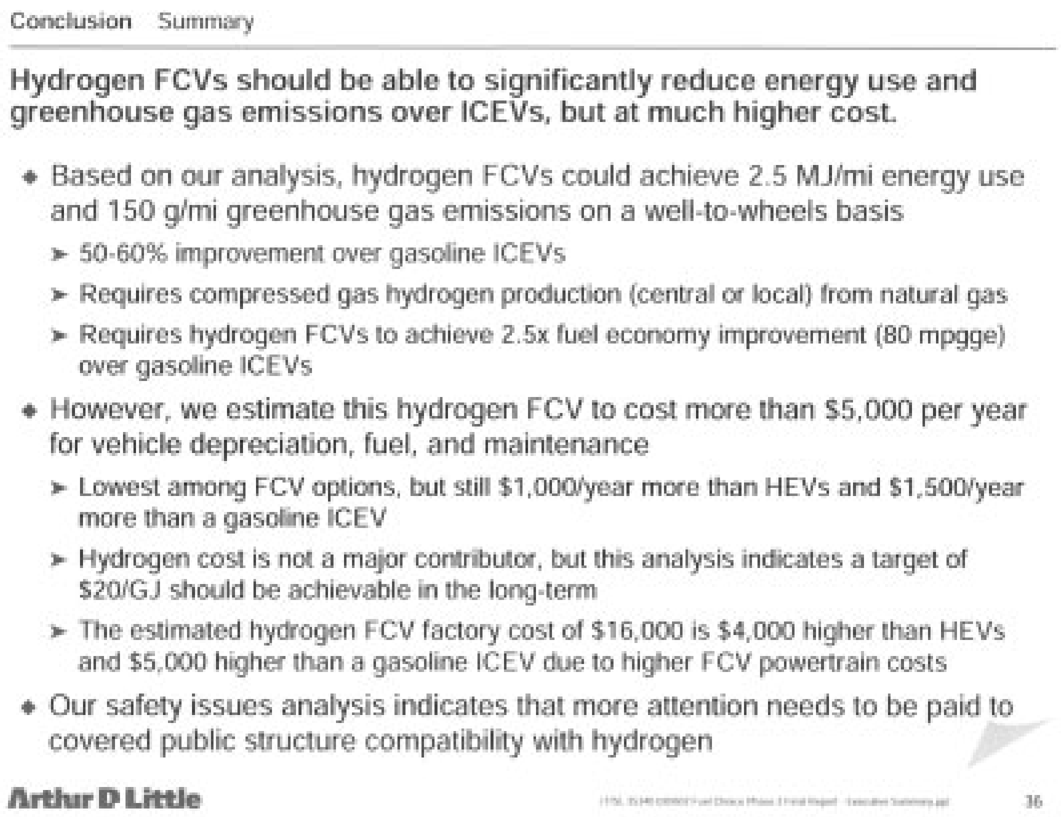

Conclusion Summary

Hydrogen FCVs should be able to significantly reduce energy use and greenhouse gas emissions over ICEVs, but at much higher cost.

- Based on our analysis, hydrogen FCVs could achieve 2.5 MJ/mi energy use and 150 g/mi greenhouse gas emissions on a well-to-wheels basis
  - 50-60% improvement over gasoline ICEVs
  - Requires compressed gas hydrogen production (central or local) from natural gas
  - Requires hydrogen FCVs to achieve 2.5x fuel economy improvement (80 mpgge) over gasoline ICEVs
- However, we estimate this hydrogen FCV to cost more than $5,000 per year for vehicle depreciation, fuel, and maintenance
  - Lowest among FCV options, but still $1,000/year more than HEVs and $1,500/year more than a gasoline ICEV
  - Hydrogen cost is not a major contributor, but this analysis indicates a target of $20/GJ should be achievable in the long-term
  - The estimated hydrogen FCV factory cost of $16,000 is $4,000 higher than HEVs and $5,000 higher than a gasoline ICEV due to higher FCV powertrain costs
- Our safety issues analysis indicates that more attention needs to be paid to covered public structure compatibility with hydrogen

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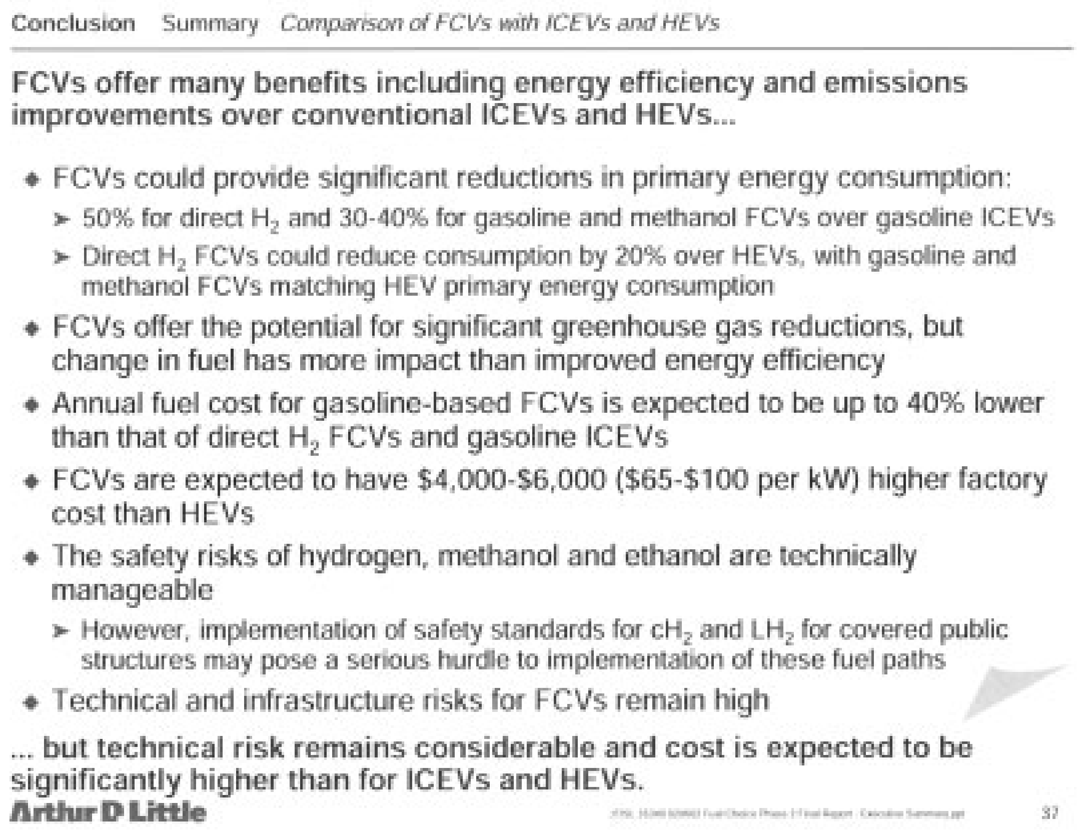

Conclusion Summary *Comparison of FCVs with ICEVs and HEVs*

FCVs offer many benefits including energy efficiency and emissions improvements over conventional ICEVs and HEVs...

- FCVs could provide significant reductions in primary energy consumption:
  - 50% for direct H_2 and 30-40% for gasoline and methanol FCVs over gasoline ICEVs
  - Direct H_2 FCVs could reduce consumption by 20% over HEVs, with gasoline and methanol FCVs matching HEV primary energy consumption
- FCVs offer the potential for significant greenhouse gas reductions, but change in fuel has more impact than improved energy efficiency
- Annual fuel cost for gasoline-based FCVs is expected to be up to 40% lower than that of direct H_2 FCVs and gasoline ICEVs
- FCVs are expected to have $4,000-$6,000 ($65-$100 per kW) higher factory cost than HEVs
- The safety risks of hydrogen, methanol and ethanol are technically manageable
  - However, implementation of safety standards for cH_2 and LH_2 for covered public structures may pose a serious hurdle to implementation of these fuel paths
- Technical and infrastructure risks for FCVs remain high

... but technical risk remains considerable and cost is expected to be significantly higher than for ICEVs and HEVs.

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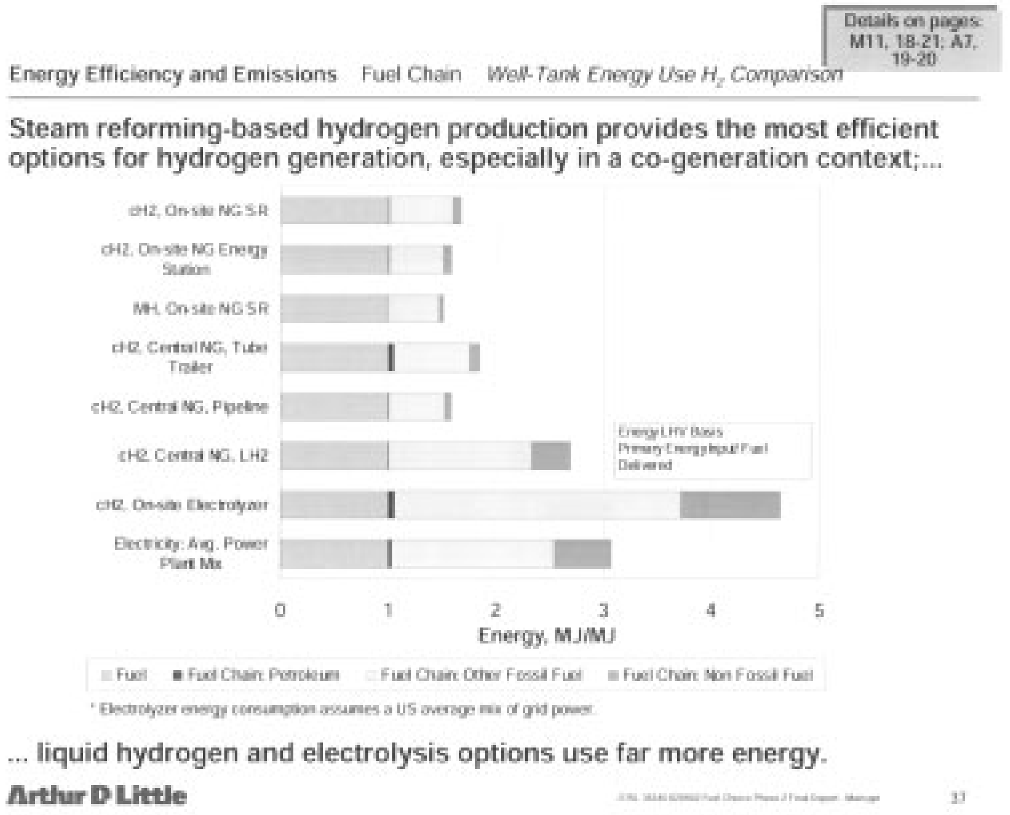
37



Details on pages: M11, 18-21; A7, 19-20

Energy Efficiency and Emissions   Fuel Chain   *Well-Tank Energy Use H_2 Comparison*

Steam reforming-based hydrogen production provides the most efficient options for hydrogen generation, especially in a co-generation context;...

* Electrolyzer energy consumption assumes a US average mix of grid power.

... liquid hydrogen and electrolysis options use far more energy.

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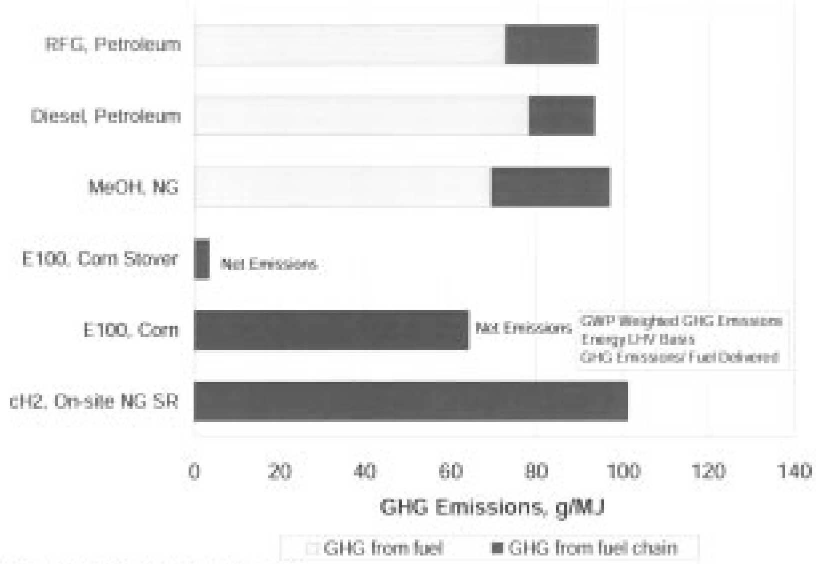
GHG emissions for hydrogen from natural gas is on par with diesel and gasoline due to the lower carbon content of the feedstock.



* Net E100 emissions include byproduct credits.

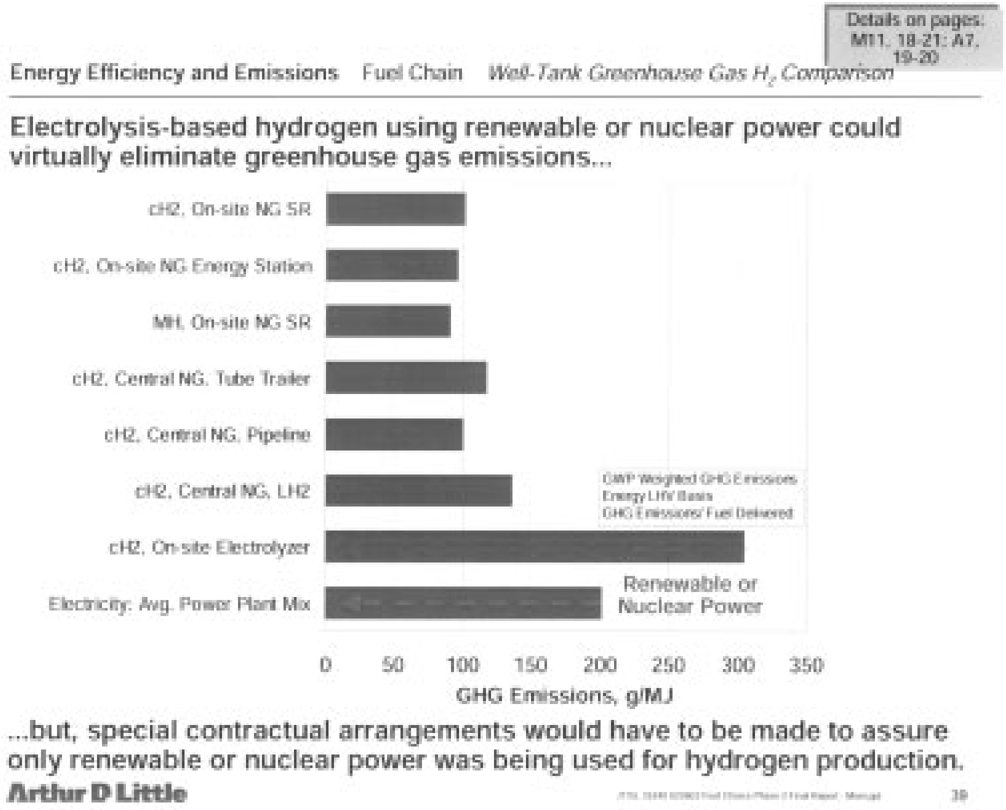
Although there are considerable differences in performance, risk, and cost of the FCV fueling options, no clear winner is identifiable.

- Compressed hydrogen FCVs could have significant benefits over reformer-based vehicles
  - 20-30% lower primary energy consumption than gasoline or methanol FCVs
  - $1,000-$2,000 ($15-$35 per kW) lower cost per vehicle; this could be increased to around around $3,500 ($60/kW) if some efficiency benefit is sacrificed
  - Significantly lower technical risk
- Reformer-based systems retain considerable benefits in terms of infrastructure risk
  - Delivered fuel costs are likely to be less than half that of hydrogen on a $/GJ basis
  - Even infrastructure investment for methanol is very modest compared to hydrogen
  - Safety issues for reformer fuels are comparatively simple to resolve, despite recent public perception of methanol's toxicity risk
- Differences between FCVs and petroleum ICEVs overwhelm differences amongst FCV options
- Hydrogen ICEVs do not appear to offer significant benefits in typical ownership cost compared with direct hydrogen FCVs
  - cH_2 ICEV range is likely to be reduced due to the large volume of hydrogen required

The detailed analysis described in this study generally supports the targets defined in Phase I, …

- Well-to-wheel energy efficiency projections based on our scenarios are generally consistent with the long-term (2008) targets suggested in Phase I
- Phase I hydrogen fuel cost targets appear difficult to achieve and the DOE should consider relaxing them
  - Given the modest impact of fuel cost on overall ownership cost
- None of the FCV future scenarios met DOE FCV cost targets of $45 per kW
- Given the performance benefits of FCVs, relaxing the target to match the cost of HEVs meeting the PZEV standard may be reasonable

… but indicates that hydrogen and FCV cost targets may be difficult to achieve without additional technology breakthroughs.



Details on pages:
M11, 18-21; A7, 19-20

Energy Efficiency and Emissions Fuel Chain *Well-Tank Greenhouse Gas H_2 Comparison*

Electrolysis-based hydrogen using renewable or nuclear power could virtually eliminate greenhouse gas emissions...

...but, special contractual arrangements would have to be made to assure only renewable or nuclear power was being used for hydrogen production.

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Outline

Main Report

Background, Objectives & Scope

Approach

Energy Efficiency and Emissions

- Fuel Chain
- **Vehicle**
- Well-to-Wheels

C

Safety

Conclusion & DOE Target Setting

Projected future scenarios lead to direct hydrogen FCVs that are technically competitive with conventional and other advanced vehicles.

- High efficiency for direct hydrogen FCVs is due to high continuous power efficiency and excellent turn-down performance
    - Reformer based FCVs have much lower part load efficiencies, but still higher than ICEVs
- Direct hydrogen FCVs could provide performance benefits over other advanced vehicle options (ICE HEVs)
    - Lower weight
    - Good low-end torque performance (electric drive)
    - Almost three times better fuel economy
- Reformate-based FCVs are more compatible with conventional fuels and could provide performance benefits over conventional vehicles (ICEVs)
    - Good low-end torque performance (electric drive)
    - Efficiency on par with hybrid electric powertrains
    - Projected efficiency could be much higher if reformer start-up and turn-down issues were solved
- The future scenarios have aggressive performance assumptions requiring success in current fuel cell system R&D activities

Details on pages: M10, 26; A56-61, 64-69

Our analysis was based on future FCV scenarios in which fuel cell technology is improved consistently with success in current R&D activities.

- An ADL/DOE analysis of a near-term technology automotive fuel cell system was used as a baseline for the projected future scenarios
  - Detailed bottom-up cost and full-load performance estimates for fuel flexible ATR FCV power unit developed for DOE Costing Program (DE-SC02-98EE50526)
- Future scenarios assume current R&D efforts are successful:
  - High-temperature, humidity-independent membranes with nafion-like conductivity are developed and the system design takes full advantage of the benefits
  - Stack platinum loading is reduced to an optimum level with high current density
  - ATR space velocities are substantially increased, improving the power density of the fuel processor
  - Fuel cell engineering is optimized, and inefficiencies are reduced or eliminated
- Key performance improvements result, in addition to cost reductions described in the next chapter:
  - Reduced weight
  - Improved system efficiency
  - Faster start-up
- The direct hydrogen FCV powertrain was not re-optimized to achieve efficiency similar to the other vehicle options; this could further reduce its weight and cost

Details on pages:
M10, 26; A56-61, 64-69

The future fuel cell system assumptions developed for the Costing program were used to estimate FCV power unit costs and performance.

Fuel Cell System Assumptions - Full Load	Units	Current Gasoline	Future Scenarios		
			Gasoline	MeOH	Hydrogen
Stack Temperature	°C	80	160	160	160
Stack Pressure	atm	3	3	3	3
Unit Cell Voltage	volts	0.8	0.8	0.8	0.8
Pt Loading (Cathode/Anode)	mg/cm²	0.4/0.4	0.2/0.1	0.2/0.1	0.2/0.1
Pt Cost	$/g	15	15	15	15
Current Density	mA/cm²	310	500	610	750
Fuel Utilization	%	85	85	85	95
Cathode Stoichiometry		2.0	2.0	2.0	2.0
Electrolyte Cost	$/m²	100	50	50	50
CEM Efficiency	% (C/E)	70/80	75/90	75/90	75/90
Total Parasitic Power	kW	6.1	3	3	3

Used in this study

We also made future assumptions for the hydrogen storage options considered in this analysis.

Baseline Direct Hydrogen FCV and ICEV Cases: compressed hydrogen storage (cH_2)

- Storage pressure: 5,000 psi*
  - We estimate a 350 mile range requires160 liters of hydrogen for a FCV and 320 liters for an ICEV
  - Conventional vehicles require 45 liters of fuel for a 350 mile range
  - We did not accommodate additional volumetric capacity in vehicle design assumptions
- Projected future cost: $265/kg hydrogen
  - Based on discussions with Quantum (IMPCO)
  - A detailed bottom-up cost analysis has not been performed to date
- Weight density: 10%
  - Based on claims by Quantum (IMPCO)
  - Numbers should be verified later this year with independent bottom-up costing

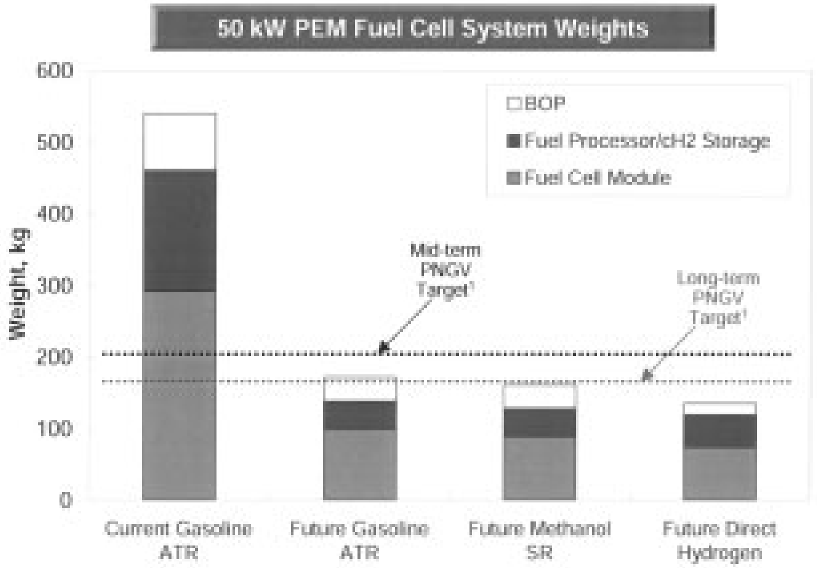
Low Pressure Direct Hydrogen FCV Case: metal hydride storage (MH)

- Projected future cost: $535/kg hydrogen
  - Internal estimate assuming a typical AB5 material
  - Includes thermal management, tank, materials and processing costs
- Projected future weight density: 4.5%
  - Likely be for some chemical hydride material - cost basis will be similar to AB5
- A detailed bottom-up cost and performance analysis has not been performed to date

* Higher pressures (10,000 psi) are being developed, but will complicate refueling systems and add on-site compressor power.

Details on pages: A56-61

The future scenarios' assumptions result in major weight reductions compared with the current technology baseline.



50 kW PEM Fuel Cell System Weights

[1] Targets established for fuel cell system with on-board fuel flexible fuel processor and balance of plant.

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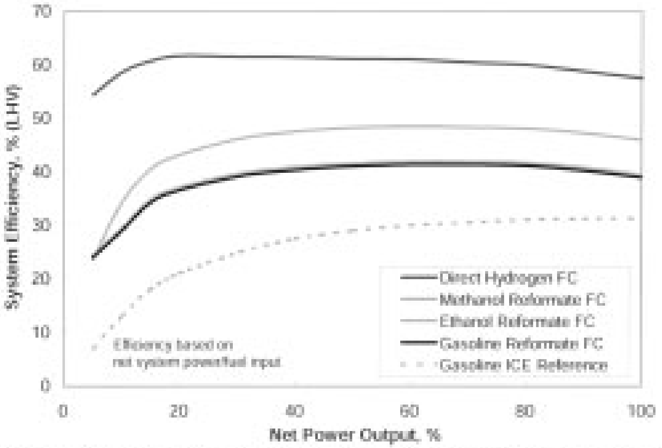
Details on pages: A40-46, 70-71, 76

Future projections for part load efficiencies were not available, so we constructed performance curves based on kinetic and thermodynamic analyses.

Power Unit Performance Curve Assumptions



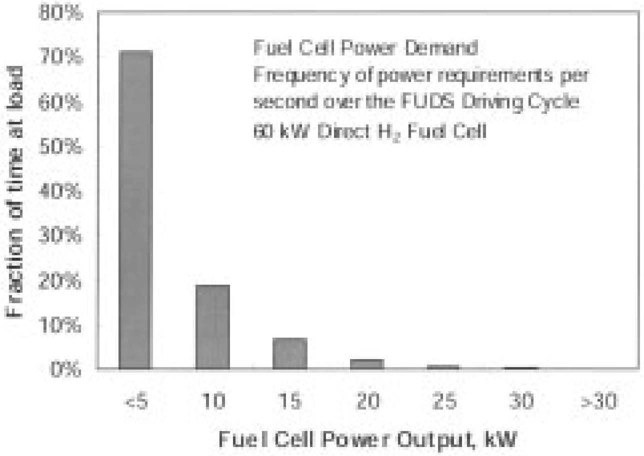
* Includes fuel cell, fuel processor (when present), and parasitic power losses. Motor and power electronic efficiencies are not included in this graph.

All FCVs have higher power unit efficiency than conventional vehicles, but high part-load efficiency sets direct hydrogen FCVs apart from all others.

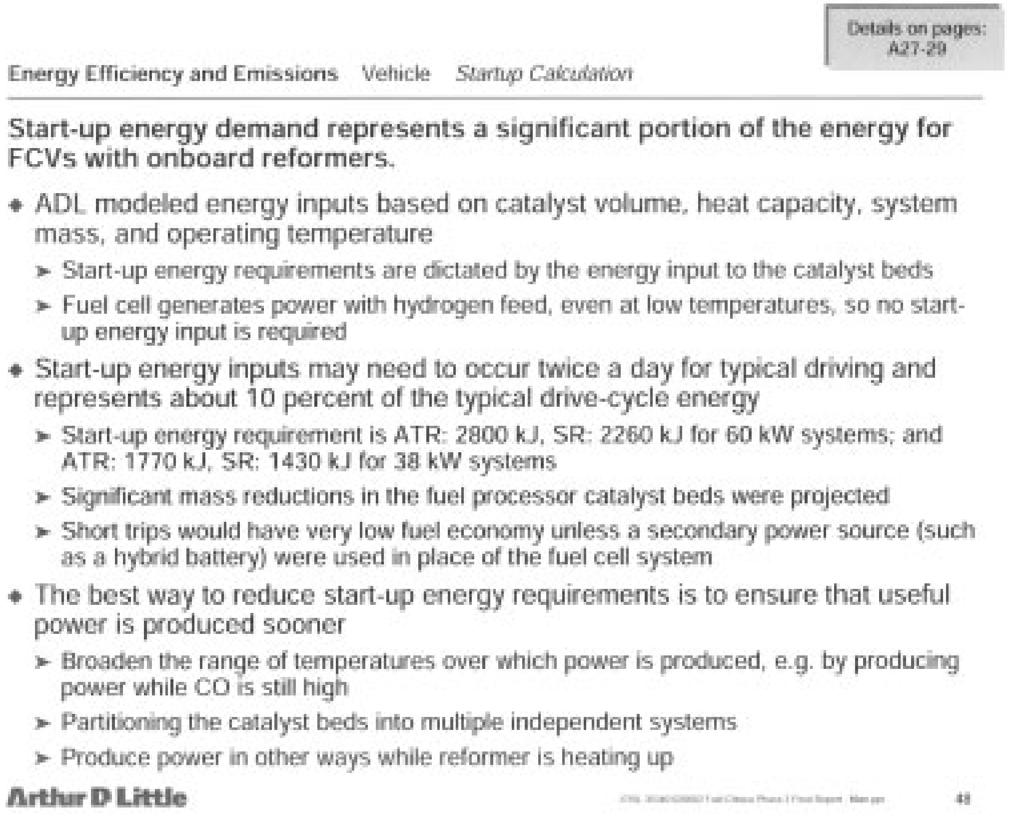
Details on pages:
A22-26

Part load efficiency is important as city driving conditions require relatively low fuel cell power output.

FUDS Power Requirements for Hydrogen FCV



Our fuel economy results are based on a combination of city (FUDS) and highway (HFET) drive cycles.



Details on pages: A27-29

Energy Efficiency and Emissions Vehicle *Startup Calculation*

Start-up energy demand represents a significant portion of the energy for FCVs with onboard reformers.

- ADL modeled energy inputs based on catalyst volume, heat capacity, system mass, and operating temperature
  - ➤ Start-up energy requirements are dictated by the energy input to the catalyst beds
  - ➤ Fuel cell generates power with hydrogen feed, even at low temperatures, so no start-up energy input is required
- Start-up energy inputs may need to occur twice a day for typical driving and represents about 10 percent of the typical drive-cycle energy
  - ➤ Start-up energy requirement is ATR: 2800 kJ, SR: 2260 kJ for 60 kW systems; and ATR: 1770 kJ, SR: 1430 kJ for 38 kW systems
  - ➤ Significant mass reductions in the fuel processor catalyst beds were projected
  - ➤ Short trips would have very low fuel economy unless a secondary power source (such as a hybrid battery) were used in place of the fuel cell system
- The best way to reduce start-up energy requirements is to ensure that useful power is produced sooner
  - ➤ Broaden the range of temperatures over which power is produced, e.g. by producing power while CO is still high
  - ➤ Partitioning the catalyst beds into multiple independent systems
  - ➤ Produce power in other ways while reformer is heating up

Arthur D Little 48

Details on pages:
A34-37

The difference in turn-down performance and weight necessitates considering different hybridization approaches for different FCVs.

- All FCVs are expected to be hybridized to some extent, even direct hydrogen FCVs
  - Simplifies start-up
  - Improves load-following characteristics
  - Improves fuel economy by storing regen braking energy
- Due to the difference in turndown characteristics and weight, the hybridization of direct hydrogen FCVs will likely be different that that of gasoline FCVs:
  - Shorter start-up time and better turndown characteristics will not require a large battery
  - However, increased regen capability resulting in potential for improved fuel economy, argues for a larger battery
- Vehicle characteristics and likely duty cycle also impact hybridization
- To explore the range of opportunities, we modeled a range of vehicle types and hybridization schemes:
  - Mid-size 5-passenger vehicle and Sport Utility vehicle (SUV)[1]
  - Small (9 kWe fixed) battery; and Large (~30 kWe variable) battery hybridization
  - For the large battery, the fuel cell power is fixed by the top speed or hill climb requirement and the battery makes up the balance required for acceleration

---

[1] SUV detailed results can be found in the appendix section "Additional Analysis Results".

Details on pages: A37-39

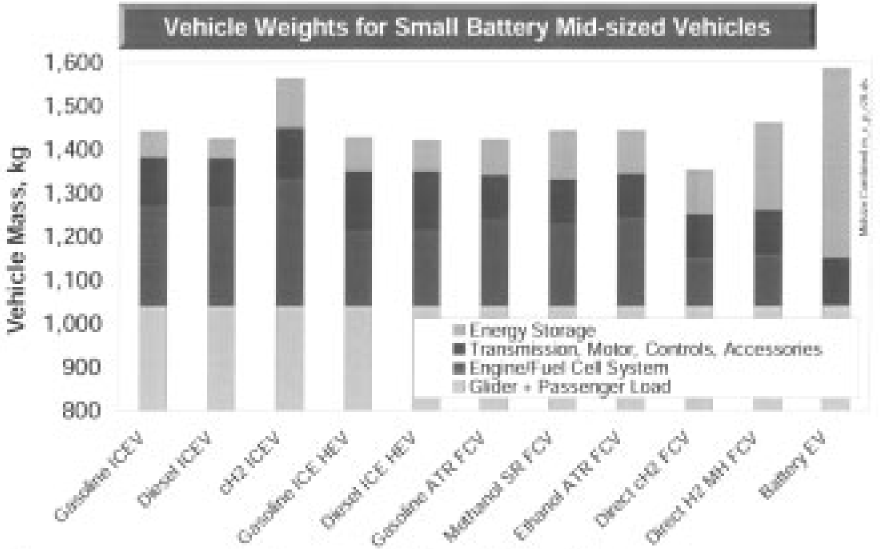
We have assumed advanced NiMH battery performance and cost for our hybrid electric and fuel cell vehicles.

- We assume NiMH hybrid battery design and duty cycle
  - ➢ Li ion batteries have not been modeled
    - ➡ potentially higher Wh/kg, higher power density, similar cost
- We assume future hybrid batteries will be $400/kWh, 750 W/kg, and 50 Wh/kg for the whole battery pack
  - ➢ Developers claim $1,000-1,500/kWh today (low production volumes)
  - ➢ Power and energy density assumptions are consistent with high end of current state-of-the art
  - ➢ PNGV HEV Specifications are 625 W/kg and 25-75 Wh/kg for PA/R batteries
- Charging and discharging efficiencies are assumed to be 85% each
  - ➢ Consistent with current hybrid battery operation

Cost optimization of the hybrid vehicle options strongly depends on the expected battery performance and cost.

Details on pages:
M12, 24-27; A23-25, 48-50, 56-62, 77

With the aggressive future assumptions, reformer-based FCVs could weigh about the same as conventional vehicles...



... but compressed-hydrogen FCVs could be lighter.

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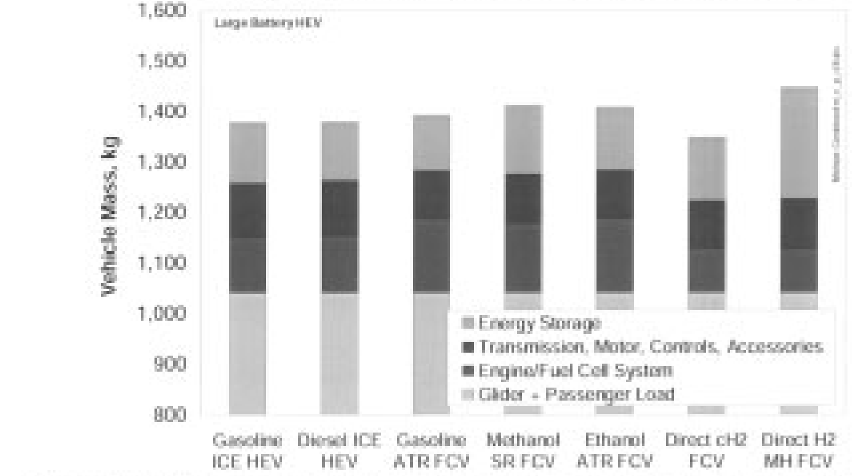
Details on pages:
M12, 24-27; A23-
25, 48-50, 56-62, 77

Energy Efficiency and Emissions Vehicle *Large Battery Mid-sized Vehicle Mass*

The large battery hybridization scheme reduces vehicle weights slightly due to drivetrain power density improvements[1].

Vehicle Weights for Large Battery Mid-sized Vehicles



[1] In the case of the FCVs, the power density (kW/kg) is higher for the battery than the fuel cell plus reformer. For the ICE HEV, the power unit changes from a V6 to an L3. The change in engines combined with the change to a continuously variable transmission (CVT) results in a small mass reduction.

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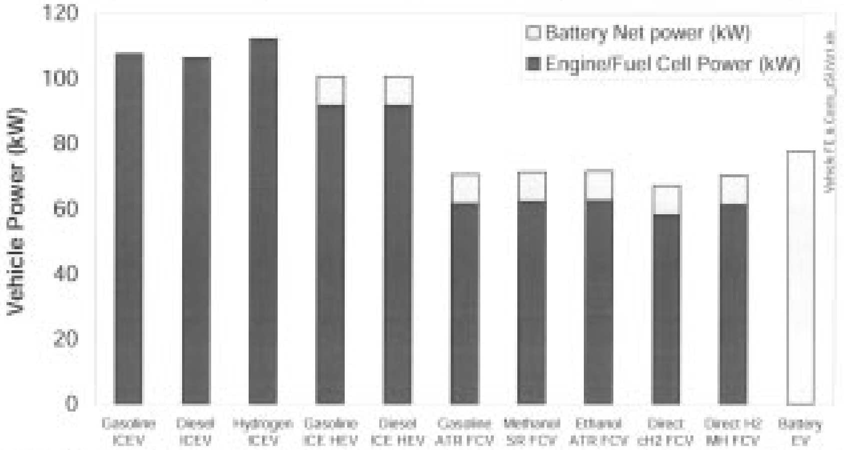
Details on pages:
M12; A34-36

Energy Efficiency and Emissions Vehicle *Small Battery Mid-sized Vehicle Power*

Vehicle maximum power requirements vary considerably due to differences in powertrain characteristics, the mass of the powertrain and the fuel.

Power Requirements for Small Battery Midsize Vehicles



ICEVs require higher peak power in order to meet low speed acceleration requirements typical for US markets*.

* Other markets may have different requirements that would change this analysis substantively

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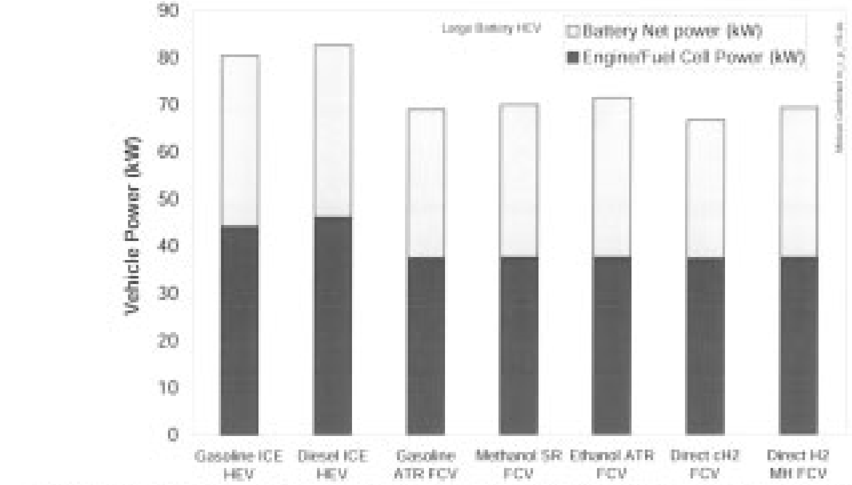
Details on pages:
M12; A34-36

Choosing a larger battery of course considerably lowers the prime mover power requirements.

Power Requirements for Large Battery Midsize Vehicles



[1] Because ICE-HEVs are expected to be parallel hybrids, they still require a relatively large engine. If the hybrids were series, the overall power would be similar to the FCVs.

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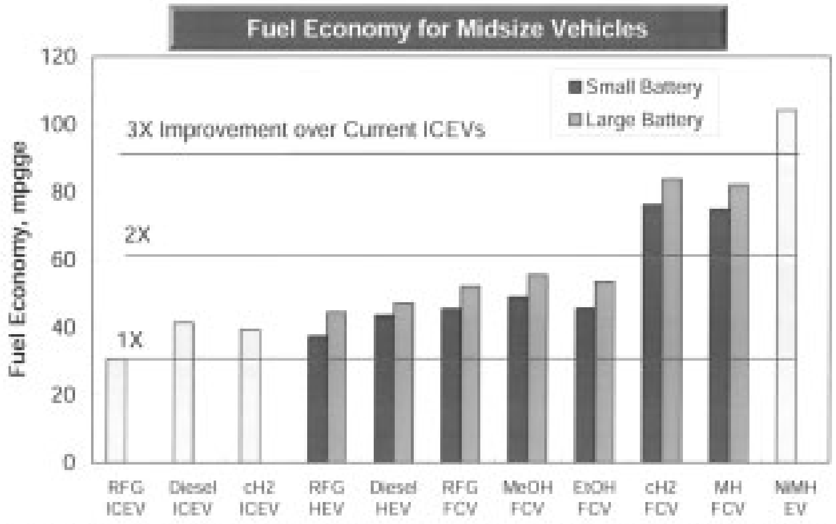
Details on pages: M12; A22-33, 78-79

Under the future scenarios, the direct hydrogen FCV gives more than 2.5 times better fuel economy than the conventional gasoline ICE vehicle.



The large battery cases give better fuel economy, due to greater regenerative braking, so we used it for the subsequent well-to-wheel analysis.

Outline

- Main Report
- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
  - Fuel Chain
  - Vehicle
  - Well-to-Wheels
- C
- Safety
- Conclusion & DOE Target Setting

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Fuel cell powertrains can achieve substantially lower well-to-wheels energy consumption than ICE-based powertrains.

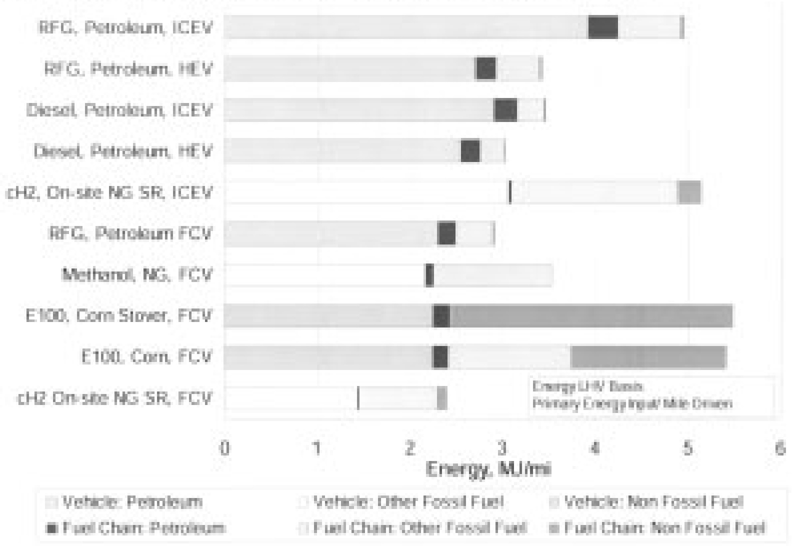
- Advanced CIDI engine vehicles using petroleum-based diesel fuel will likely be able to achieve similar energy efficiency to gasoline reformer-based FCVs
  - ➢ Methanol FCVs have higher well-to-wheels energy consumption, despite high vehicle efficiency, due to significant losses incurred in fuel production
- The inefficiency of ethanol production leads to well-to-wheel primary energy consumption for ethanol FCVs slightly above that of conventional vehicles
  - ➢ Primary fossil fuel consumption is of course strongly reduced
- Compressed hydrogen FCV options via centralized or decentralized production from natural gas can provide the most fuel efficient options:
  - ➢ Provided hydrogen production facilities are thermally well-integrated
  - ➢ Provided high vehicle fuel economy can be attained
  - ➢ If transportation distances from the central plant are modest (50 miles or less) using pipeline or tube trailers
- Hydrogen via electrolysis and battery EV options have high well-to-wheels energy consumption due to the relative inefficiency of power generation

Hydrogen-fueled FCVs are likely to provide the lowest greenhouse gas emissions of the non-renewable fuel chain options.

- Direct hydrogen FCVs can cut greenhouse gas emissions by 60% compared with conventional gasoline-fuel ICEVs
  - Integrated fuel production from natural gas (low-carbon fuel) leads to modest fuel production emissions
  - Vehicle greenhouse gas emissions are zero
  - Advanced diesel CIDI vehicles can achieve about half of this emissions reduction
- Gasoline and methanol FCVs have higher greenhouse gas emissions than most direct hydrogen fuel chains but lower than all ICE-based fuel chains
- In other studies, we found that greenhouse gas emissions could be reduced by over eighty percent if the right renewable energy sources are applied:
  - Hydrogen from electrolysis using wind, solar, or biomass power
  - Bio-ethanol from advanced cellulosic processes

Details on pages:
M11-12

On a well-to-wheels basis, direct hydrogen FCVs may reduce energy consumption by more than 50% over gasoline ICEVs...



... and gasoline reformer FCVs offer a 40% reduction.

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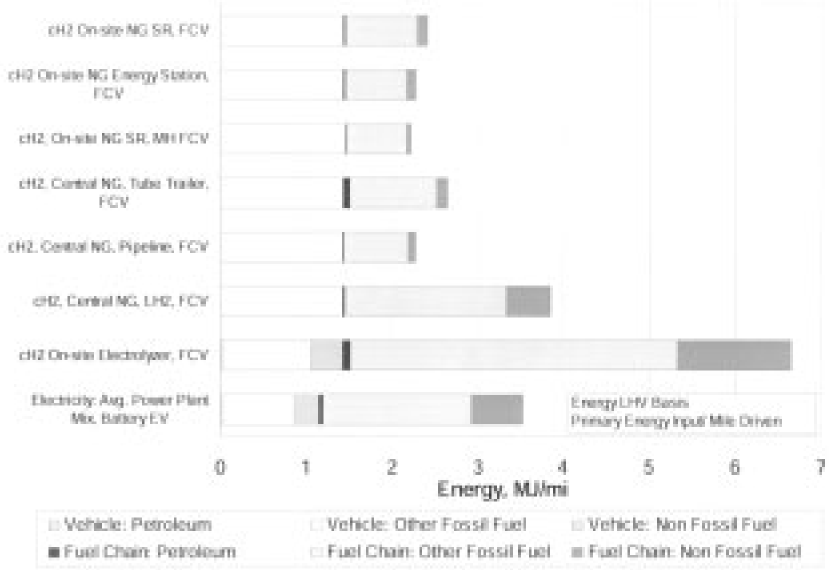
Details on pages:
M11-12

Hydrogen via electrolysis and battery EV options have high energy consumption due to the relative inefficiency of power generation.



* Electrolyzer energy consumption assumes a US average mix of grid power.

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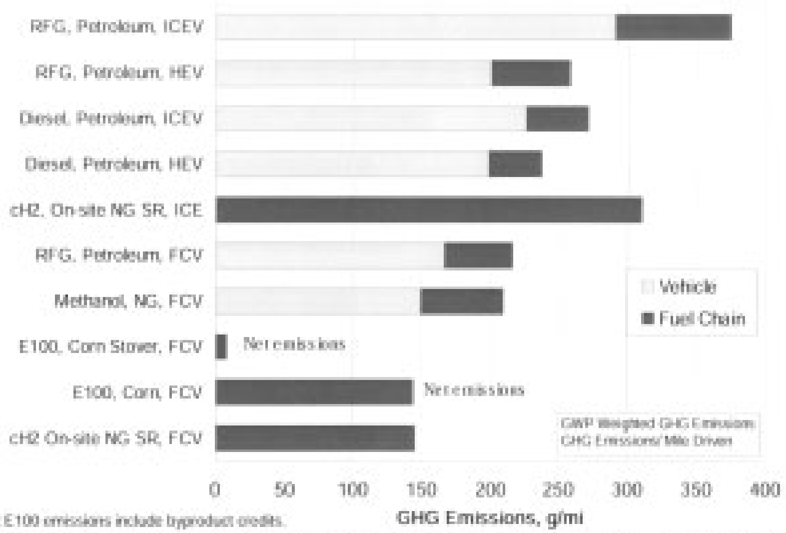
Details on pages: M11-12

Energy Efficiency and Emissions Well-to-Wheels *Greenhouse Gas Fuel Comparison*

On a well-to-wheels basis, natural gas based direct hydrogen FCVs could reduce greenhouse gas emissions by 60% compared with gasoline ICEVs...



* Net E100 emissions include byproduct credits.

... comparable to current ethanol technology but still far higher than advanced (cellulosic) ethanol technology options.

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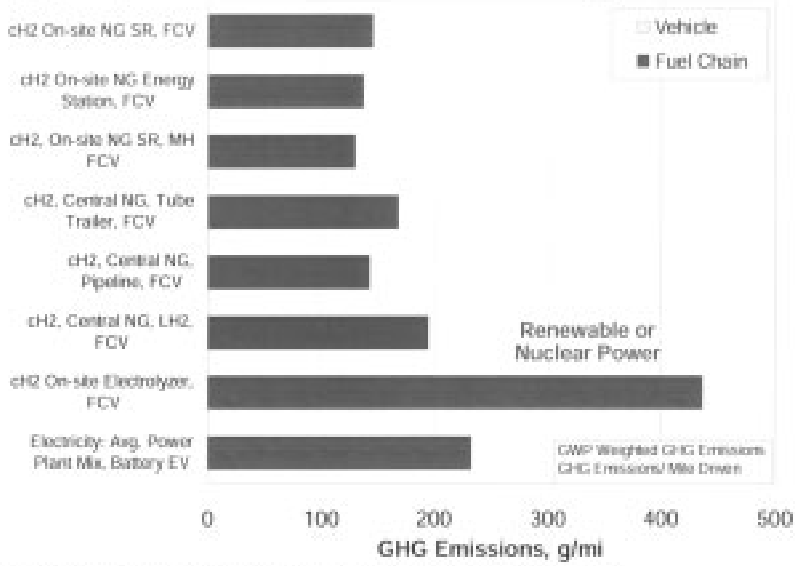
Details on pages:
M11-12

Energy Efficiency and Emissions Well-to-Wheels *Greenhouse Gas Hydrogen Options*

The lowest GHG emissions can be achieved by direct hydrogen vehicles using hydrogen made from renewable or nuclear power…



… even considerably lower than renewable ethanol.

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Outline

Main Report

- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- **Cost**
- Safety
- Conclusion & DOE Target Setting

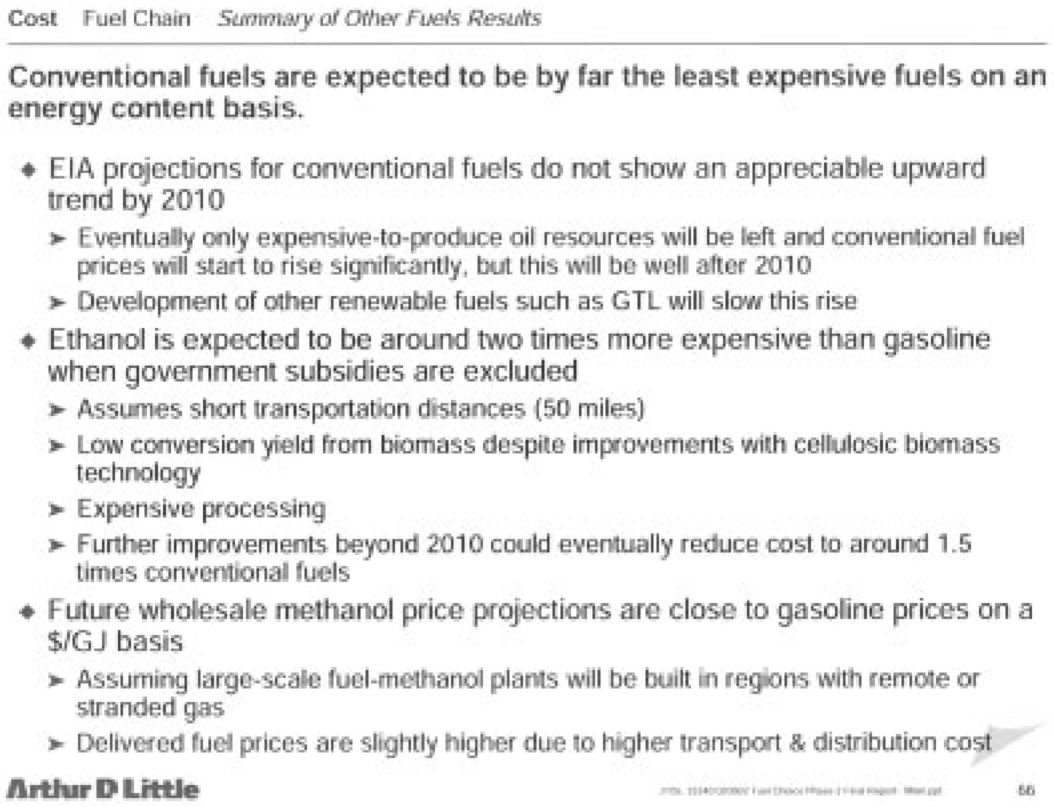
Outline

Main Report

- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- Cost
  - Fuel Chain
  - Vehicle
  - Well-to-Wheels
- S
- Concl

The most economical hydrogen fuel chains are expected to be over two times more expensive than gasoline, on a $/GJ basis.

- Capital costs are five to ten times more expensive than gasoline capital costs (including local and central plant capital)
  - Limitations in maximum train size (compared with refineries) and system complexity lead to high central plant capital cost
- Transportation and distribution costs (including compression and storage) are far higher than those for gasoline
- High feedstock cost dominates the high cost of locally produced hydrogen
- Electrolyzer-based production is costly with EIA energy price projections
  - Competitive with natural gas based reforming only if industrial electricity rates ($0.04/kWh) can be obtained at local fueling stations
  - When off-peak electric power is used, electrolysis equipment cost is higher because of low equipment utilization
- Alternative fuels, especially hydrogen, will require a significant upfront investment, representing a risk to both vehicle manufacture and fuel provider
  - Dealing with this risk represents a formidable barrier to the use of hydrogen for FCVs



Conventional fuels are expected to be by far the least expensive fuels on an energy content basis.

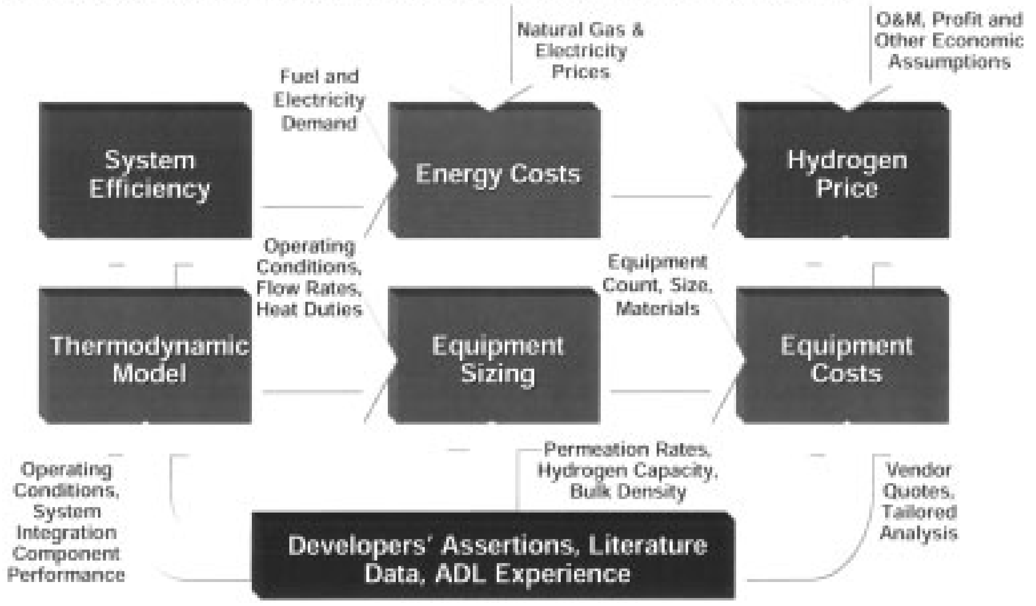
- EIA projections for conventional fuels do not show an appreciable upward trend by 2010
  - Eventually only expensive-to-produce oil resources will be left and conventional fuel prices will start to rise significantly, but this will be well after 2010
  - Development of other renewable fuels such as GTL will slow this rise
- Ethanol is expected to be around two times more expensive than gasoline when government subsidies are excluded
  - Assumes short transportation distances (50 miles)
  - Low conversion yield from biomass despite improvements with cellulosic biomass technology
  - Expensive processing
  - Further improvements beyond 2010 could eventually reduce cost to around 1.5 times conventional fuels
- Future wholesale methanol price projections are close to gasoline prices on a $/GJ basis
  - Assuming large-scale fuel-methanol plants will be built in regions with remote or stranded gas
  - Delivered fuel prices are slightly higher due to higher transport & distribution cost

Details on pages:
M22; A7, 14-17

Fuel costs are based on EIA price projections and on bottom-up estimates for hydrogen and other alternative fuels.

- Conventional fuel and electricity costs are based on EIA commodity price projections for 2010
  - Gasoline and diesel prices are based EIA projections for crude oil and historical price spreads between petroleum products and crude oil
- For non-hydrogen alternative fuels, bottom-up analyses from previous Arthur D. Little studies were used
  - Methanol costs relied on extensive GTL analyses performed for a range of studies vetted by several key methanol industry players
  - Ethanol costs are based on a previous ADL Biomass study and *The USDA 1998 US Ethanol Cost of Production Survey* (Shapouri, 1999)
- Costs of hydrogen are based on bottom-up cost analysis following the fuel chain analysis:
  - Fuel and electricity costs are estimated based on commodity price forecasts and fuel chain energy inputs
  - Local fueling station capital costs are based on modeling and vendor quotes adjusted for higher production volumes (100 units/yr) using progress ratios
  - Transportation and central plant capital costs are based on published data
  - Corporate expenses and other costs are consistent with industry practice
- Fuel sales and excise taxes are excluded

Thermodynamic modeling helped determine overall hydrogen costs by providing energy requirements and equipment sizing inputs.



System Efficiency

Thermodynamic Model

Fuel and Electricity Demand

Operating Conditions, Flow Rates, Heat Duties

Natural Gas & Electricity Prices

Energy Costs

Equipment Sizing

Equipment Count, Size, Materials

O&M, Profit and Other Economic Assumptions

Hydrogen Price

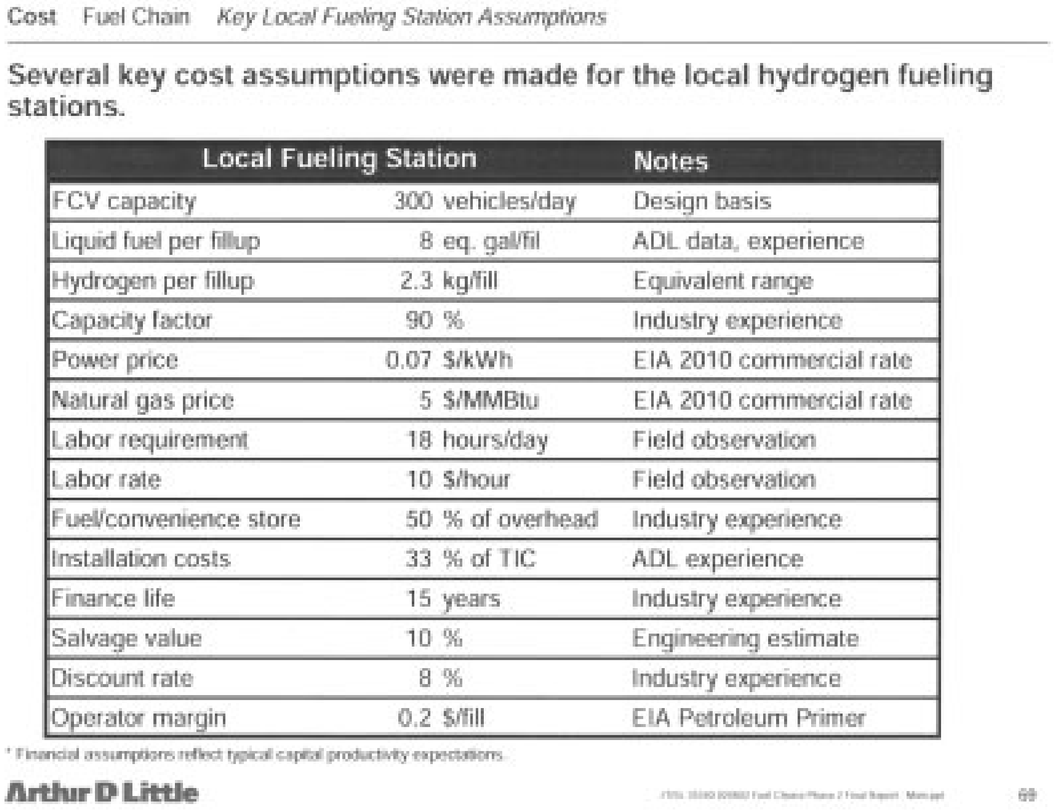
Equipment Costs

Operating Conditions, System Integration Component Performance

Permeation Rates, Hydrogen Capacity, Bulk Density

Vendor Quotes, Tailored Analysis

Developers' Assertions, Literature Data, ADL Experience



Several key cost assumptions were made for the local hydrogen fueling stations.

Local Fueling Station		Notes
FCV capacity	300 vehicles/day	Design basis
Liquid fuel per fillup	8 eq. gal/fil	ADL data, experience
Hydrogen per fillup	2.3 kg/fill	Equivalent range
Capacity factor	90 %	Industry experience
Power price	0.07 $/kWh	EIA 2010 commercial rate
Natural gas price	5 $/MMBtu	EIA 2010 commercial rate
Labor requirement	18 hours/day	Field observation
Labor rate	10 $/hour	Field observation
Fuel/convenience store	50 % of overhead	Industry experience
Installation costs	33 % of TIC	ADL experience
Finance life	15 years	Industry experience
Salvage value	10 %	Engineering estimate
Discount rate	8 %	Industry experience
Operator margin	0.2 $/fill	EIA Petroleum Primer

* Financial assumptions reflect typical capital productivity expectations.

A different set of cost assumptions were made for the central hydrogen plant options.

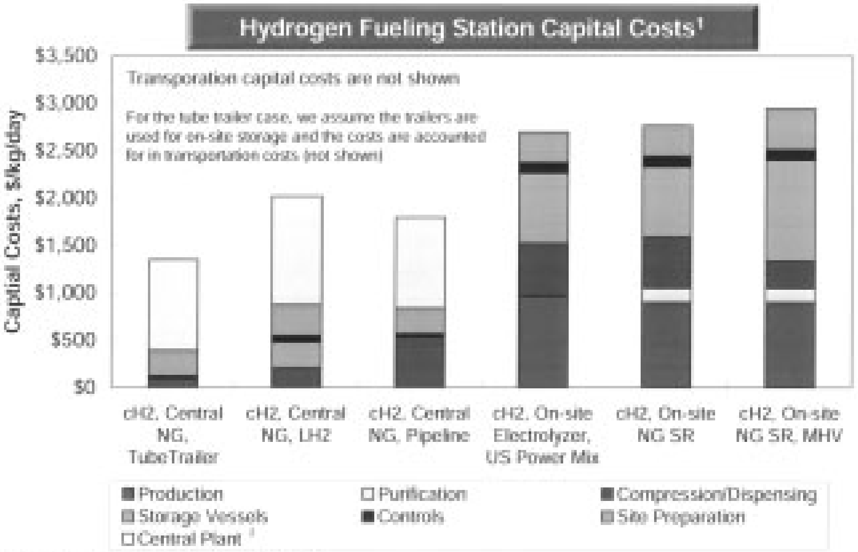
Central Hydrogen Plant			Notes
Daily Production	300	tonne H2/day	Design basis
Stream days	330		Industry experience
Power price	0.04	$/kWh	EIA 2010 industrial rate
Natural gas price	3	$/MMBtu	EIA 2010 industrial rate
Finance life	10	years	Industry experience
Salvage value	10	%	Engineering estimate
Discount rate	11	%	ADL experience
Operator profit	0.15	$/kg H2	Engineering estimate
Truck transport distance	50	miles	Assumed for urban area

* Financial assumptions reflect typical capital productivity expectations.

Details on pages: A14, 16

Cost Fuel Chain *Fueling Station Capital Costs*

Local fueling station capital costs are significant, ranging from $300,000 to $2 million per station, far outstripping franchise owners' resources.



Hydrogen Fueling Station Capital Costs[1]

[1] Fueling station capacity is 690 kg hydrogen/day.

[2] Central plant capital costs are shown for comparison, but are not part of the fueling station cost

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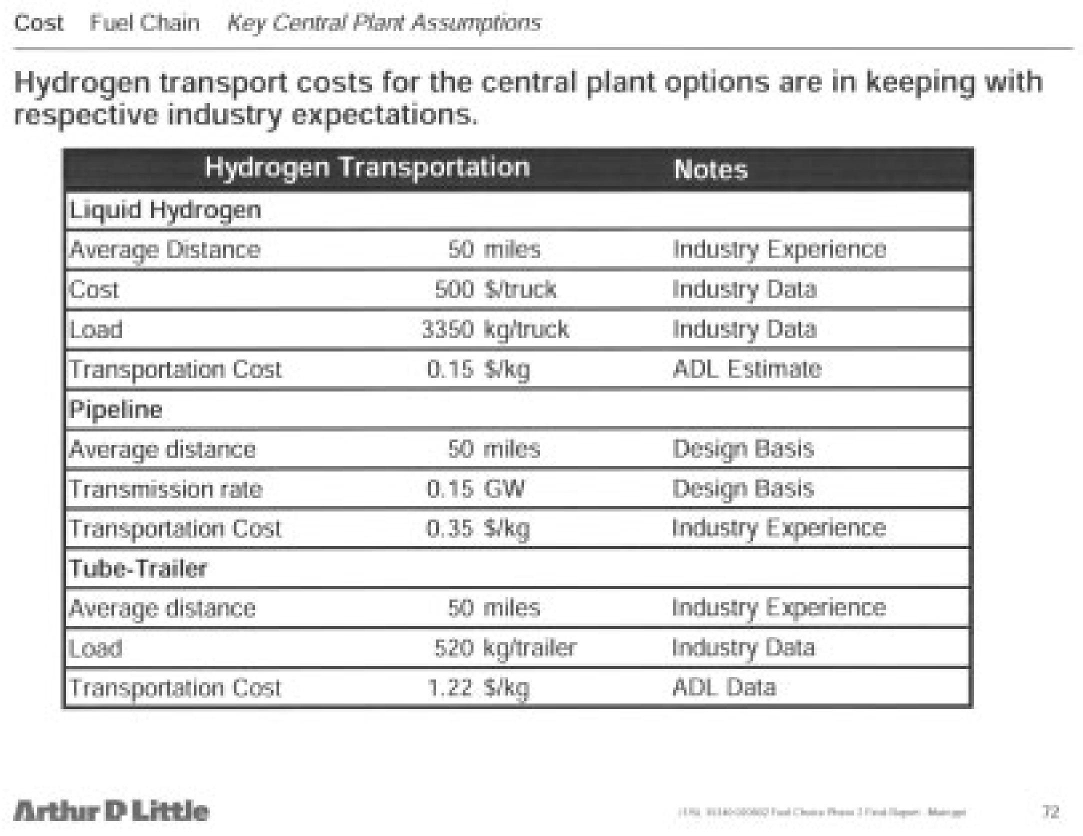

Cost Fuel Chain *Key Central Plant Assumptions*

Hydrogen transport costs for the central plant options are in keeping with respective industry expectations.

Hydrogen Transportation		Notes
Liquid Hydrogen		
Average Distance	50 miles	Industry Experience
Cost	500 $/truck	Industry Data
Load	3350 kg/truck	Industry Data
Transportation Cost	0.15 $/kg	ADL Estimate
Pipeline		
Average distance	50 miles	Design Basis
Transmission rate	0.15 GW	Design Basis
Transportation Cost	0.35 $/kg	Industry Experience
Tube-Trailer		
Average distance	50 miles	Industry Experience
Load	520 kg/trailer	Industry Data
Transportation Cost	1.22 $/kg	ADL Data

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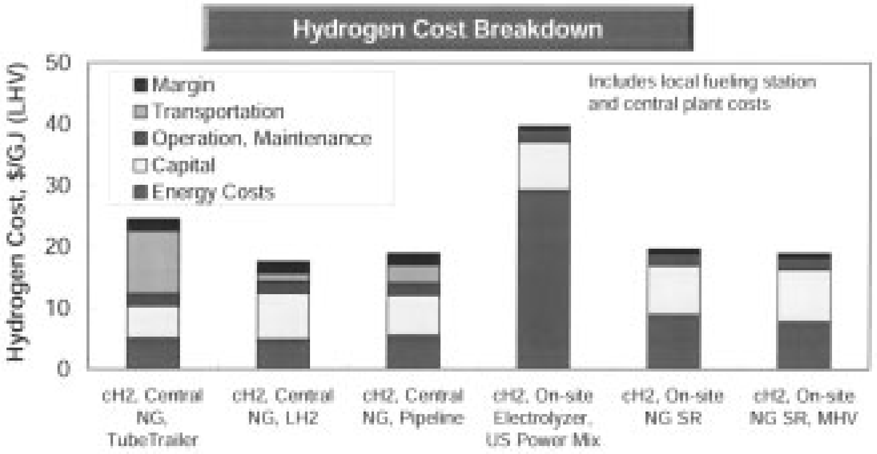
Details on pages:
A7, 14, 16

Cost Fuel Chain *Hydrogen Results*

Most hydrogen production options range in cost (before taxes) from about $15 to $25/GJ.



- Central plant costs were calculated based on internal and published values for energy demands and costs for capital, O&M, profit, and transportation
- Local fueling station operating costs and profit are consistent with current gasoline stations
- Local electricity and natural gas prices are assume to be 2010 EIA projected commercial rates of $0.07/kWh and $5/MMBtu, respectively

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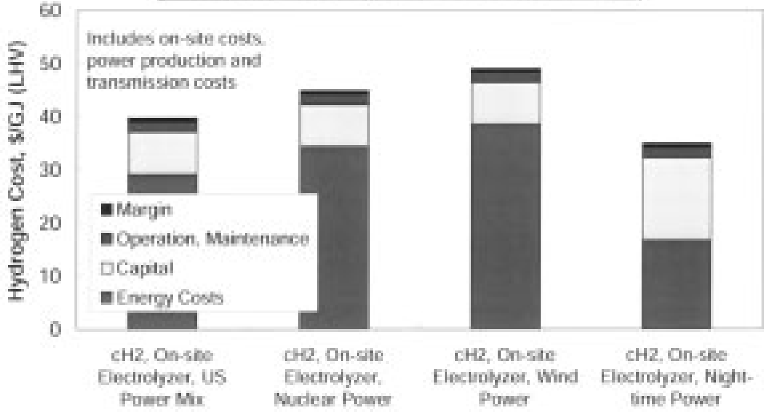
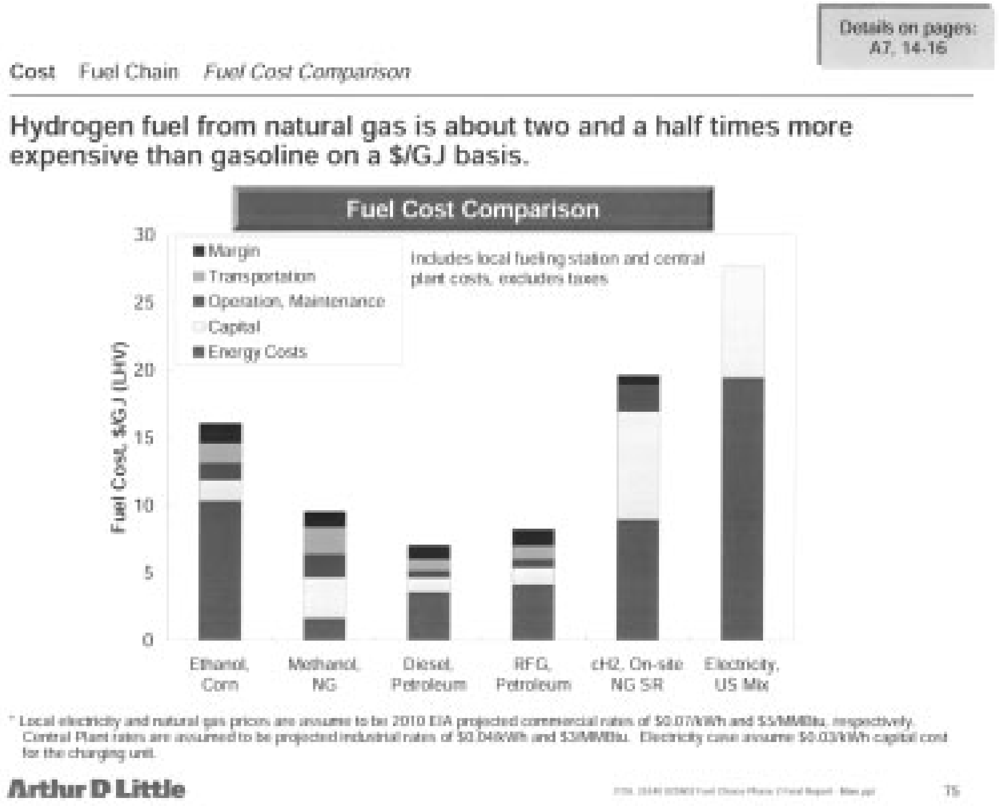
Details on pages:
A14,16-17

Even with optimistic assumptions on renewable and nuclear power cost, electrolysis-based hydrogen would be more expensive than natural gas based hydrogen.

On-site Electrolyzer Cost Breakdown



- US Power Mix, Nuclear, and Wind electricity prices are assumed to be 0.07, 0.08, and 0.09 $/kWh
- The night-time power case assumes the use of cheap off-peak renewable power for $0.04/kWh
  - Energy costs are much lower, but capital cost of this case is higher due to a reduced capacity factor



Details on pages: A7, 14-16

Cost Fuel Chain *Fuel Cost Comparison*

Hydrogen fuel from natural gas is about two and a half times more expensive than gasoline on a $/GJ basis.

Fuel Cost Comparison

* Local electricity and natural gas prices are assume to be 2010 EIA projected commercial rates of $0.07/kWh and $5/MMBtu, respectively. Central Plant rates are assumed to be projected industrial rates of $0.04/kWh and $3/MMBtu. Electricity case assume $0.03/kWh capital cost for the charging unit.

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Details on pages:
A94-101

We analyzed the uncertainty in fuel costs with a Monte Carlo simulation of input variables.

Factor Influencing Cost	Basis for Uncertainty Estimate
Input Fuel Prices[1]	Lognormal distribution with standard deviations based on historical fuel prices (See Appendix)
Fueling Station Costs	Assumed +/- 15% uncertainty due to fuel transportation and fueling station costs (capital, operation, and maintenance)
Power Generation Capital Costs	Assumed +/- 15% uncertainty in wind and nuclear power capital costs for the on-site electrolizer scenarios

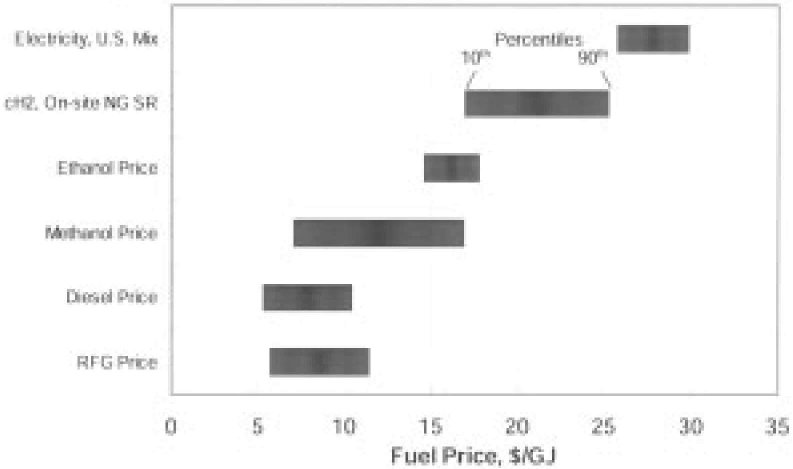
[1] The input fuel to the SR based hydrogen fueling stations or central production facilities is natural gas. Electricity is the input fuel for electrolyzers.

Details on pages:
A94-101

Cost Fuel Chain *Sensitivity Analysis Results*

Even taking into account possible variations in fuel cost; electricity, hydrogen and ethanol are likely to be substantially more expensive than gasoline...

Sensitivity Analysis - Fuel Costs (LHV)



... while methanol may be competitive with gasoline and diesel in certain scenarios.

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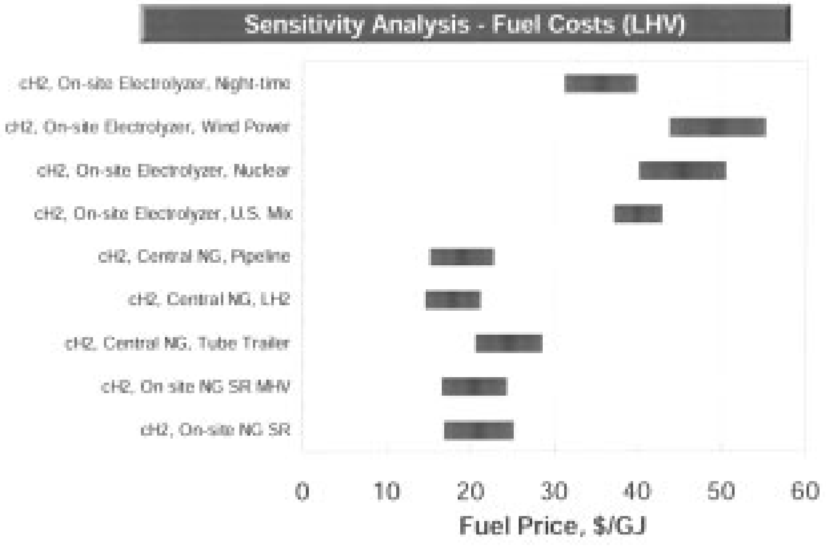
Details on pages: A94-101

Cost Fuel Chain *Sensitivity Analysis - Hydrogen*

Uncertainty over electric power costs exacerbates the high cost of hydrogen from electrolyzers.


Sensitivity Analysis - Fuel Costs (LHV)

Outline

Main Report

Background, Objectives & Scope

Approach

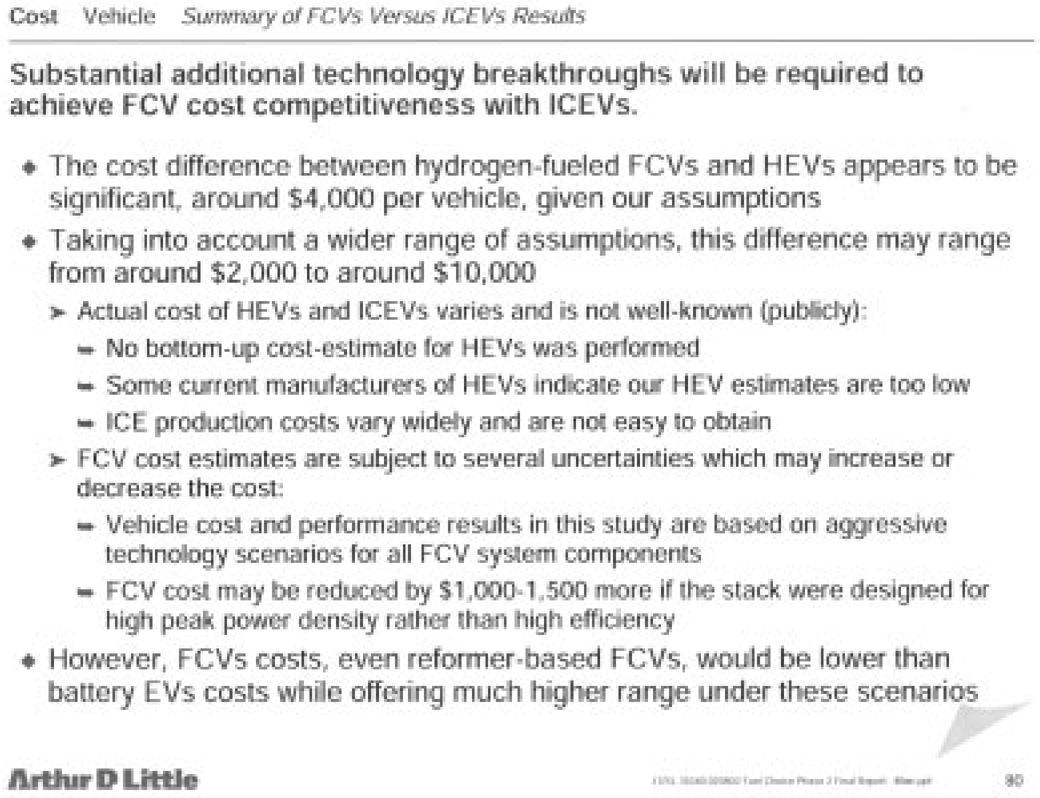
Energy Efficiency and Emissions

Cost

- Fuel Chain
- **Vehicle**
- Well-to-Wheels

S

Concl



Substantial additional technology breakthroughs will be required to achieve FCV cost competitiveness with ICEVs.

- The cost difference between hydrogen-fueled FCVs and HEVs appears to be significant, around $4,000 per vehicle, given our assumptions
- Taking into account a wider range of assumptions, this difference may range from around $2,000 to around $10,000
  - Actual cost of HEVs and ICEVs varies and is not well-known (publicly):
    - No bottom-up cost-estimate for HEVs was performed
    - Some current manufacturers of HEVs indicate our HEV estimates are too low
    - ICE production costs vary widely and are not easy to obtain
  - FCV cost estimates are subject to several uncertainties which may increase or decrease the cost:
    - Vehicle cost and performance results in this study are based on aggressive technology scenarios for all FCV system components
    - FCV cost may be reduced by $1,000-1,500 more if the stack were designed for high peak power density rather than high efficiency
- However, FCVs costs, even reformer-based FCVs, would be lower than battery EVs costs while offering much higher range under these scenarios

The cost and performance of the fuel cell stack remains the key barrier in achieving cost parity with HEVs or conventional vehicles.

- The additional cost being projected for FCVs over conventional and HEV platforms is clearly significant
  - Current FCV power unit cost is 2-3 times the DOE/PNGV target of $45/kW
  - System components not counted in the $45/kW target further increase difference in cost with ICEVs
  - By using different assumptions, the gap could be reduced but would remain significant
- The differences in cost between various FCV fuel choices is significant, but does not appear deciding compared to the difference with ICEVs
- Stack remains key to further improving the cost of FCVs
  - Stack cost by itself remains the largest FCV power unit component
  - Power density, CO tolerance, and other performance limitations determine the need for other subsystems
- However, in order to further reduce FCV cost, the cost of other subsystems and components will also need to be addressed
  - Future scenarios for motor and power electronics costs are nearly as expensive as the fuel cell stack

Powertrain costs for compressed-hydrogen FCVs would be significantly lower than those of systems with on-board reformers in our scenarios.

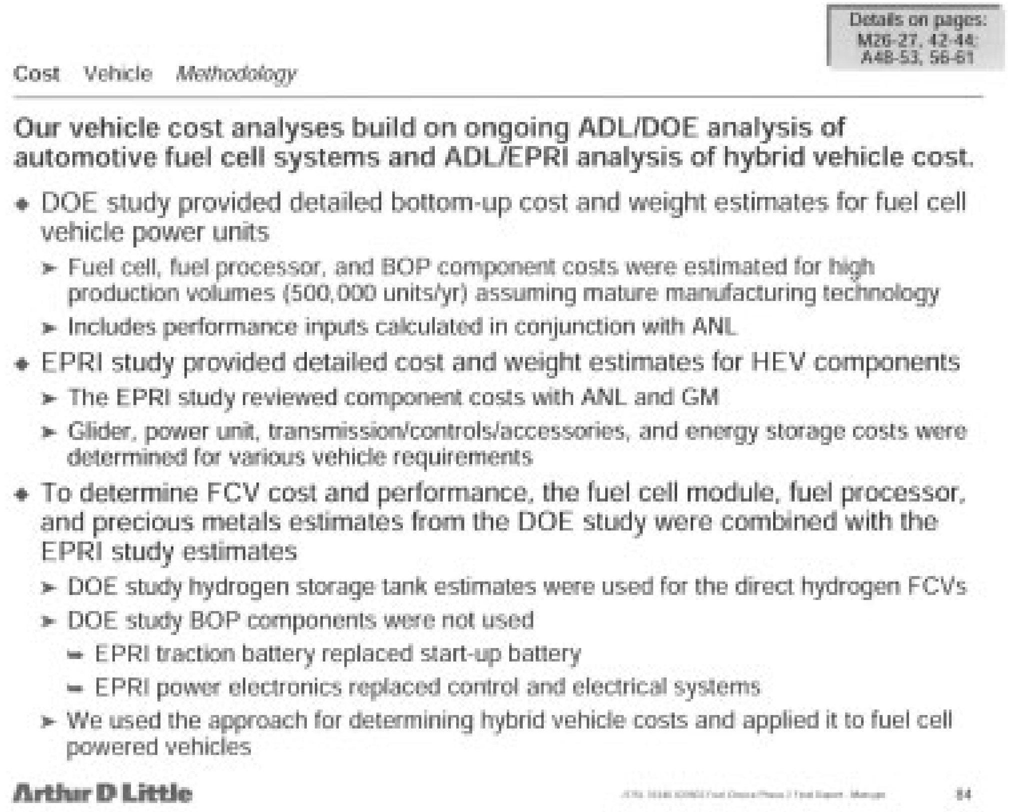
- Fuel processor-based FCVs are projected to cost \$1,000-\$2,000 more than compressed cH_2 vehicles:
  - Fuel processors add cost directly
  - Fuel processors add weight, which increases power requirements to achieve desired performance, thus adding to entire power unit cost
  - Reformers impact the performance of the fuel cell stack, and cause its cost to increase:
    - Due to poorer fuel quality of reformate (compared with pure hydrogen), including dilution and poisoning effects (CO and S), reformer-based fuel cell stacks must be larger or have higher platinum loadings
    - The reformer losses significantly impact the well-to-wheel efficiency; if direct hydrogen FCVs were optimized to achieve the same efficiency, their cost could be reduced further (this was not done for this study)
- Fuel processor-based FCVs would cost roughly the same as metal hydride-based FCVs

Nevertheless, the difference in cost does not appear decisive by itself in light of the difference in cost between all FCVs and HEVS and ICEVs.

Cost of methanol steam reformer-based FCVs are somewhat lower than those of gasoline/ethanol ATR-based FCVs.

- Methanol steam reformer itself is somewhat less complex than gasoline or ethanol ATR:
  - ➢ Maximum operating temperature is much lower, simplifying heat integration
  - ➢ High temperature shift reactor (or equivalent) can be avoided
- Methanol steam reformer produces somewhat higher quality reformate:
  - ➢ No nitrogen diluent means the hydrogen partial pressure almost equals that of hydrogen systems (after anode humidification)
  - ➢ CO control (if needed, unlike with our HTM assumption) would be somewhat easier
- Methanol reformers carry lower technical risk and cost than gasoline reformers:
  - ➢ Multiple in-vehicle demonstrations of methanol technology under way
  - ➢ On-board reforming of gasoline or ethanol in vehicle demonstration has not been accomplished yet (GM plans for next year)

The differences between reformer-based options appear modest compared with implications of differences in infrastructure and technology risks.



Details on pages:
M26-27, 42-44;
A48-53, 56-61

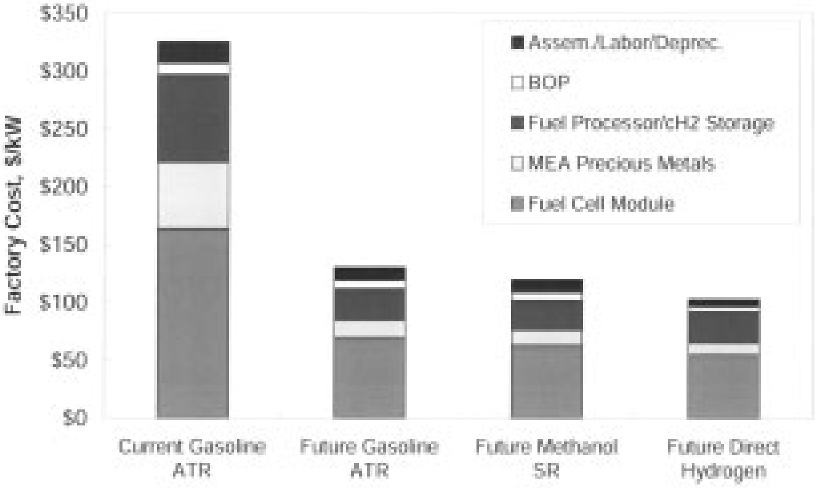
Our vehicle cost analyses build on ongoing ADL/DOE analysis of automotive fuel cell systems and ADL/EPRI analysis of hybrid vehicle cost.

- DOE study provided detailed bottom-up cost and weight estimates for fuel cell vehicle power units
  - Fuel cell, fuel processor, and BOP component costs were estimated for high production volumes (500,000 units/yr) assuming mature manufacturing technology
  - Includes performance inputs calculated in conjunction with ANL
- EPRI study provided detailed cost and weight estimates for HEV components
  - The EPRI study reviewed component costs with ANL and GM
  - Glider, power unit, transmission/controls/accessories, and energy storage costs were determined for various vehicle requirements
- To determine FCV cost and performance, the fuel cell module, fuel processor, and precious metals estimates from the DOE study were combined with the EPRI study estimates
  - DOE study hydrogen storage tank estimates were used for the direct hydrogen FCVs
  - DOE study BOP components were not used
    - EPRI traction battery replaced start-up battery
    - EPRI power electronics replaced control and electrical systems
  - We used the approach for determining hybrid vehicle costs and applied it to fuel cell powered vehicles

Details on pages: M26, 42-44; A56-61

The future scenario assumptions used in this analysis have more than halved the fuel cell system costs projected for the current baseline system.

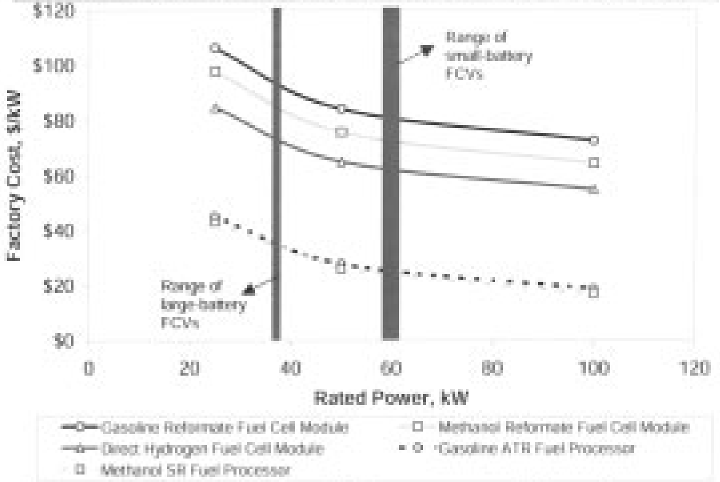
50 kW PEM Fuel Cell System Factory Costs



Details on pages: M53-54

Significant changes in FC power unit costs on a $/kW basis over the actual system output were estimated and taken into account for this analysis.

Scaled PEM Fuel Cell and Fuel Processor Factory Costs

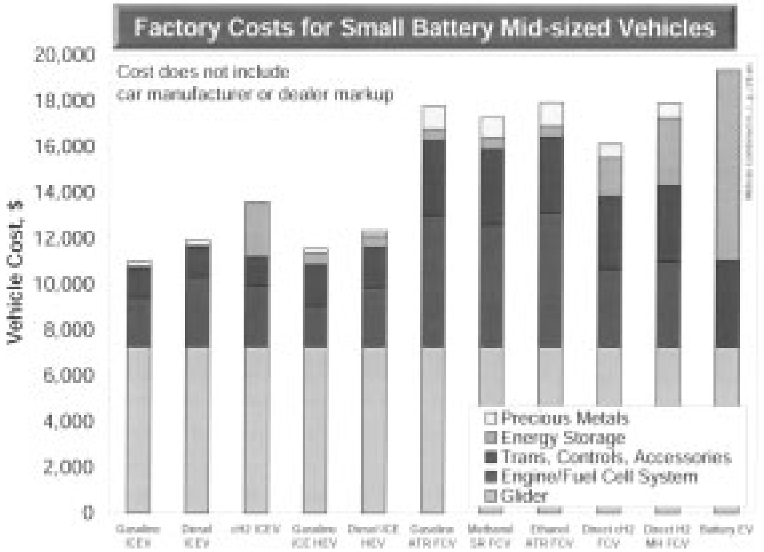


Small and large battery hybrid vehicle power unit costs are proportional to these curves.

Details on pages:
M12, 25; A49-52,
80-81

Cost Vehicle *Factory Cost - Small Battery*

Based on our scenario analysis, factory costs of future FCVs would likely be 40-60% higher than conventional vehicles, but lower than battery EVs.



Note: All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

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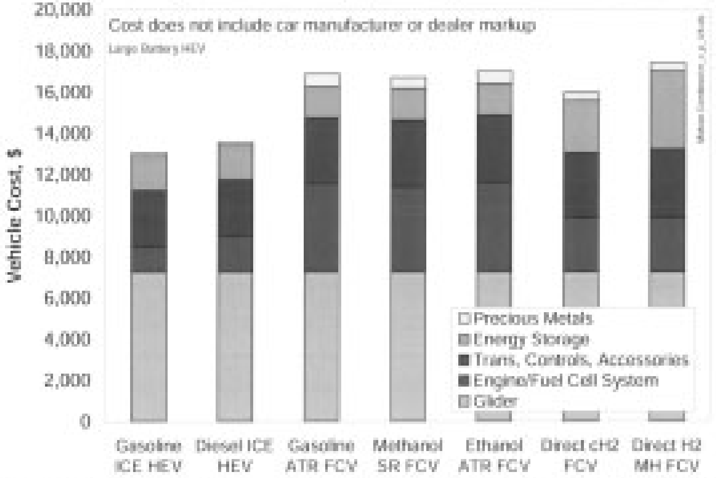
Details on pages: M12, 25; A49-52, 80-81

Cost Vehicle *Factory Cost - Large Battery*

Given our battery cost assumptions, heavier hybridization would provide cost reduction, in addition to fuel economy benefits for FCVs...

Factory Costs for Large Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

... while it would increase ICE-based HEV cost.

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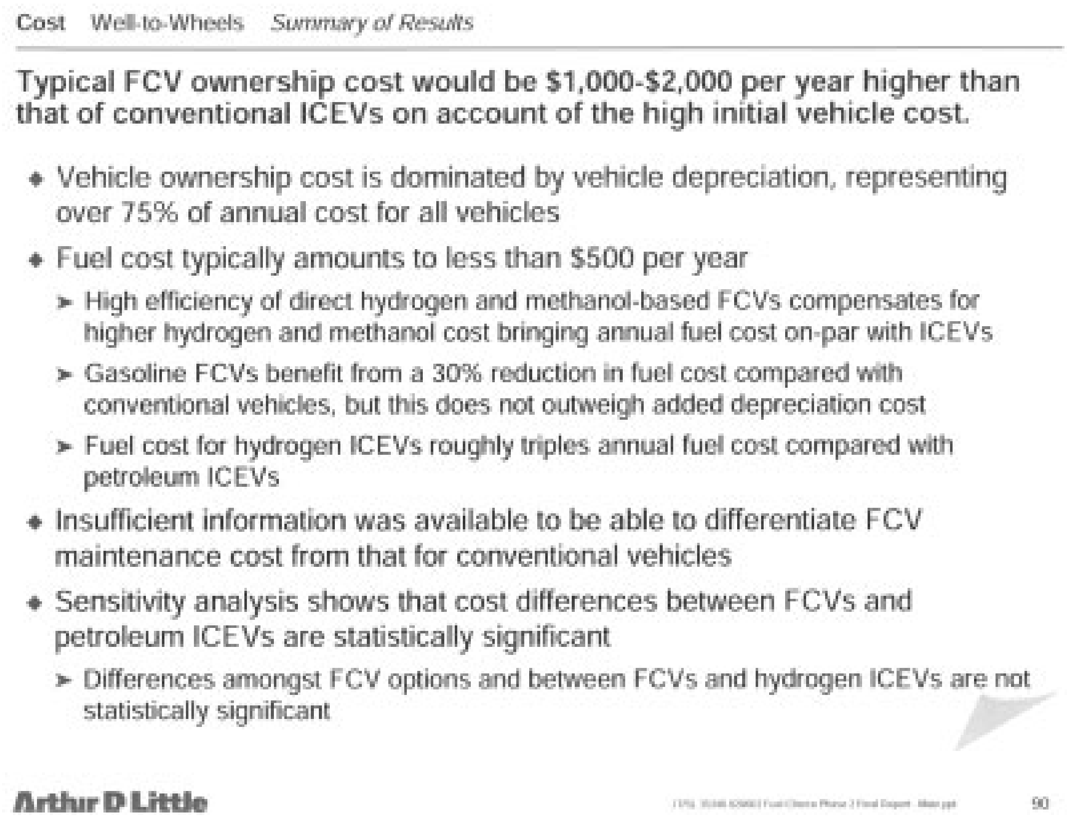
Outline

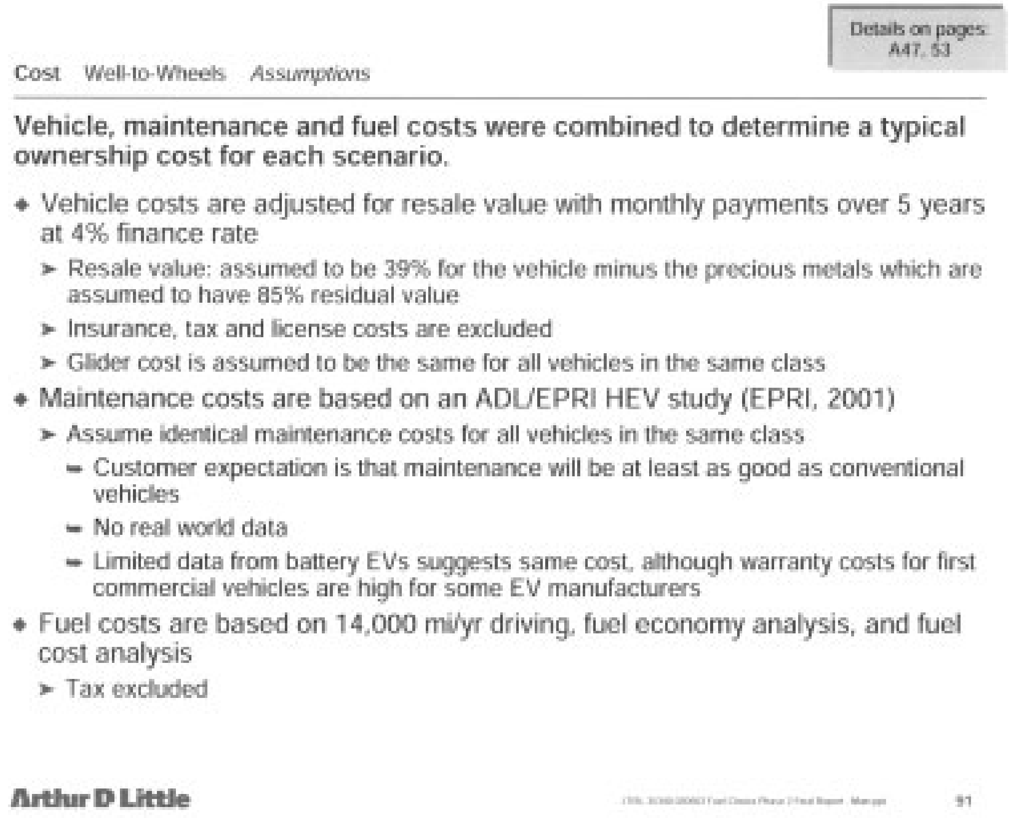
Main Report

- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- **Cost**
  - Fuel Chain
  - Vehicle
  - **Well-to-Wheels**
- S
- Concl



Typical FCV ownership cost would be $1,000-$2,000 per year higher than that of conventional ICEVs on account of the high initial vehicle cost.

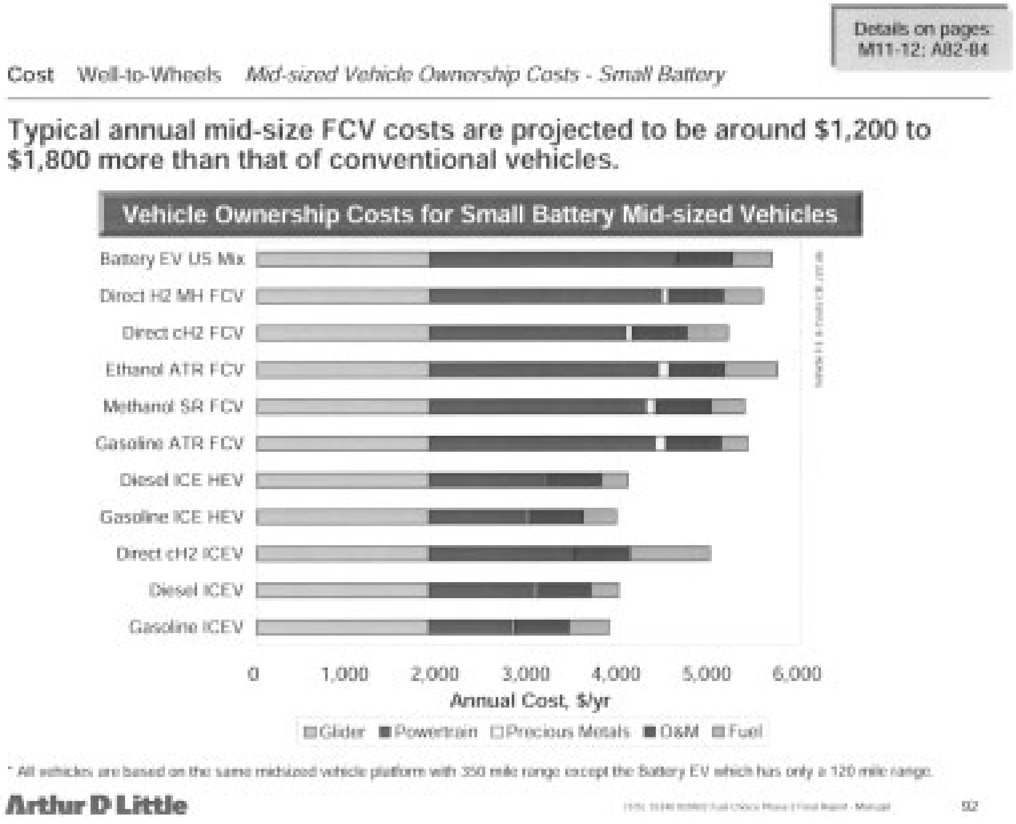
- Vehicle ownership cost is dominated by vehicle depreciation, representing over 75% of annual cost for all vehicles
- Fuel cost typically amounts to less than $500 per year
  - High efficiency of direct hydrogen and methanol-based FCVs compensates for higher hydrogen and methanol cost bringing annual fuel cost on-par with ICEVs
  - Gasoline FCVs benefit from a 30% reduction in fuel cost compared with conventional vehicles, but this does not outweigh added depreciation cost
  - Fuel cost for hydrogen ICEVs roughly triples annual fuel cost compared with petroleum ICEVs
- Insufficient information was available to be able to differentiate FCV maintenance cost from that for conventional vehicles
- Sensitivity analysis shows that cost differences between FCVs and petroleum ICEVs are statistically significant
  - Differences amongst FCV options and between FCVs and hydrogen ICEVs are not statistically significant



Details on pages: A47, 53

Vehicle, maintenance and fuel costs were combined to determine a typical ownership cost for each scenario.

- Vehicle costs are adjusted for resale value with monthly payments over 5 years at 4% finance rate
  - Resale value: assumed to be 39% for the vehicle minus the precious metals which are assumed to have 85% residual value
  - Insurance, tax and license costs are excluded
  - Glider cost is assumed to be the same for all vehicles in the same class
- Maintenance costs are based on an ADL/EPRI HEV study (EPRI, 2001)
  - Assume identical maintenance costs for all vehicles in the same class
    - Customer expectation is that maintenance will be at least as good as conventional vehicles
    - No real world data
    - Limited data from battery EVs suggests same cost, although warranty costs for first commercial vehicles are high for some EV manufacturers
- Fuel costs are based on 14,000 mi/yr driving, fuel economy analysis, and fuel cost analysis
  - Tax excluded



Details on pages: M11-12; A82-84

Cost Well-to-Wheels *Mid-sized Vehicle Ownership Costs - Small Battery*

Typical annual mid-size FCV costs are projected to be around $1,200 to $1,800 more than that of conventional vehicles.

Vehicle Ownership Costs for Small Battery Mid-sized Vehicles

* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

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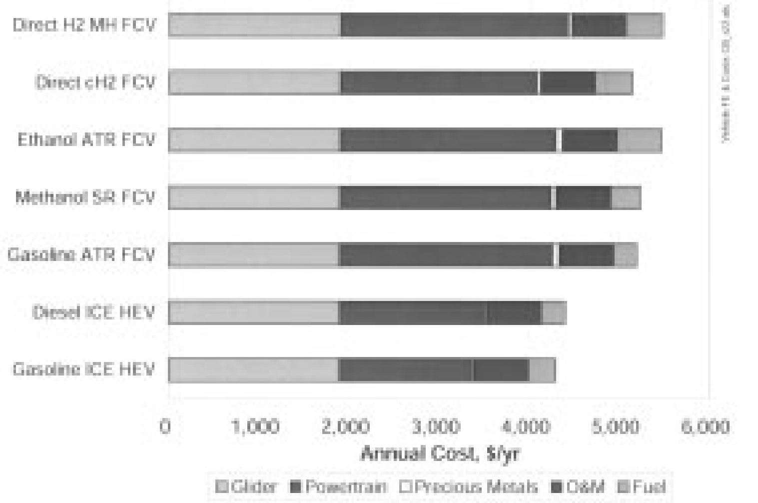
92

Details on pages: M11-12; A82-84

Cost Well-to-Wheels *Mid-sized Vehicle Ownership Costs - Large Battery*

A high degree of hybridization of FCVs could reduce FCV annual operating cost by several hundred dollars, while increasing HEV cost by the same.

Vehicle Ownership Costs for Large Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range.

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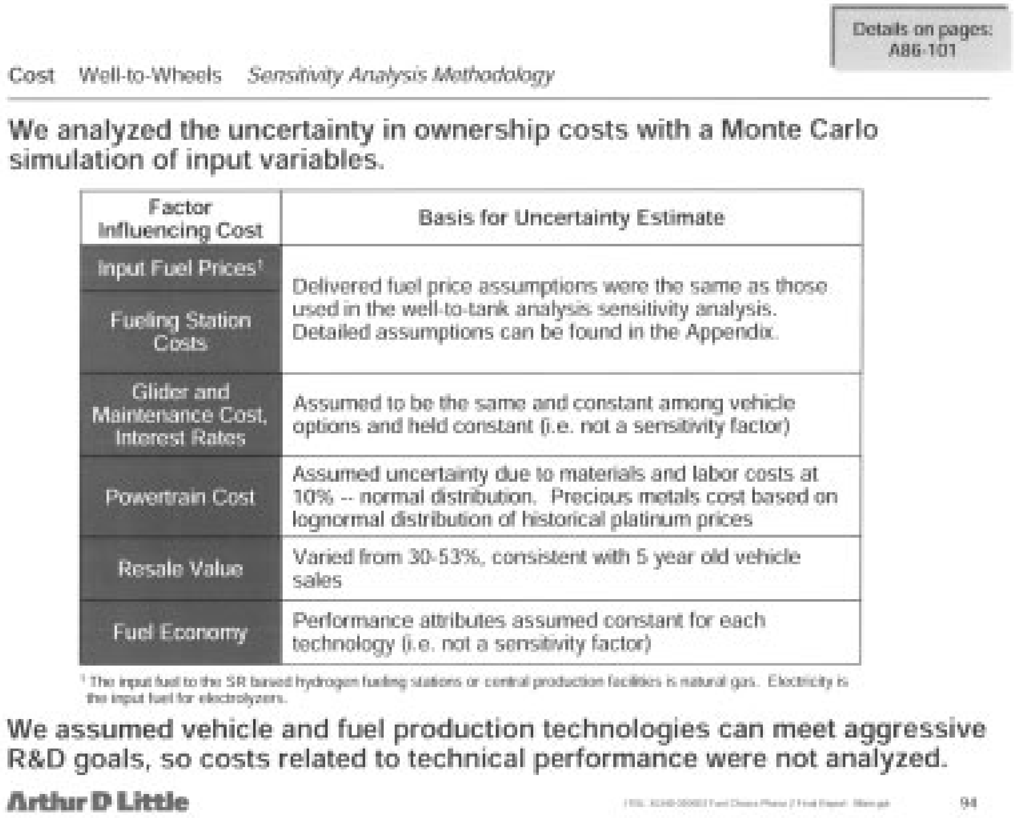


Details on pages:
A86-101

We analyzed the uncertainty in ownership costs with a Monte Carlo simulation of input variables.

Factor Influencing Cost	Basis for Uncertainty Estimate
Input Fuel Prices[1]	Delivered fuel price assumptions were the same as those used in the well-to-tank analysis sensitivity analysis. Detailed assumptions can be found in the Appendix.
Fueling Station Costs	
Glider and Maintenance Cost, Interest Rates	Assumed to be the same and constant among vehicle options and held constant (i.e. not a sensitivity factor)
Powertrain Cost	Assumed uncertainty due to materials and labor costs at 10% -- normal distribution. Precious metals cost based on lognormal distribution of historical platinum prices
Resale Value	Varied from 30-53%, consistent with 5 year old vehicle sales
Fuel Economy	Performance attributes assumed constant for each technology (i.e. not a sensitivity factor)

[1] The input fuel to the SR based hydrogen fueling stations or central production facilities is natural gas. Electricity is the input fuel for electrolyzers.

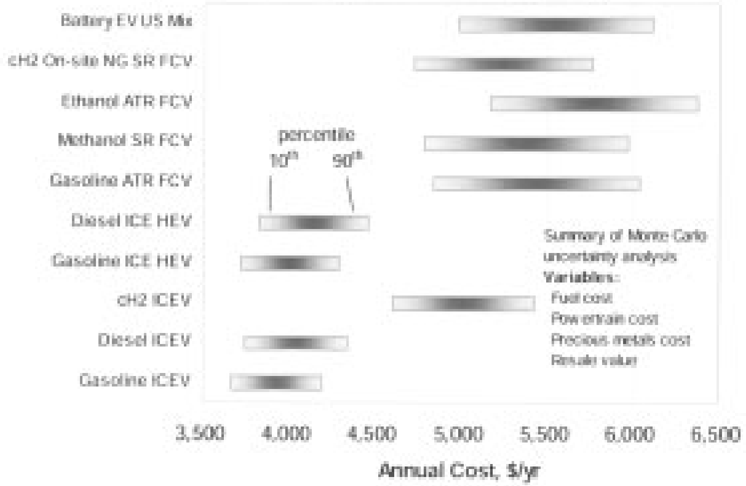
We assumed vehicle and fuel production technologies can meet aggressive R&D goals, so costs related to technical performance were not analyzed.

Details on pages: A86-101

Cost Well-to-Wheels *Sensitivity Analysis Results*

Our sensitivity analysis confirms that the difference in ownership cost between FCVs and petroleum ICEVs is statistically significant...

Ownership Cost Sensitivity Analysis

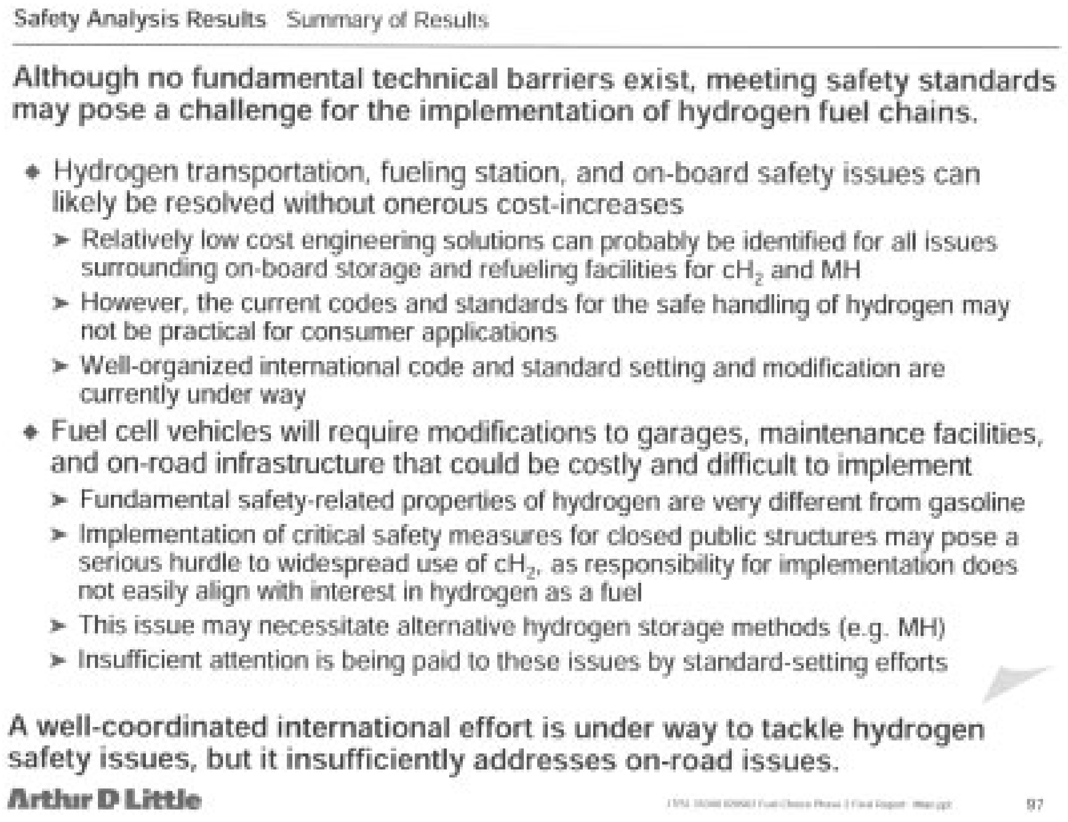


... but that the difference amongst FCVs and hydrogen ICEVs is not.

Outline

Main Report

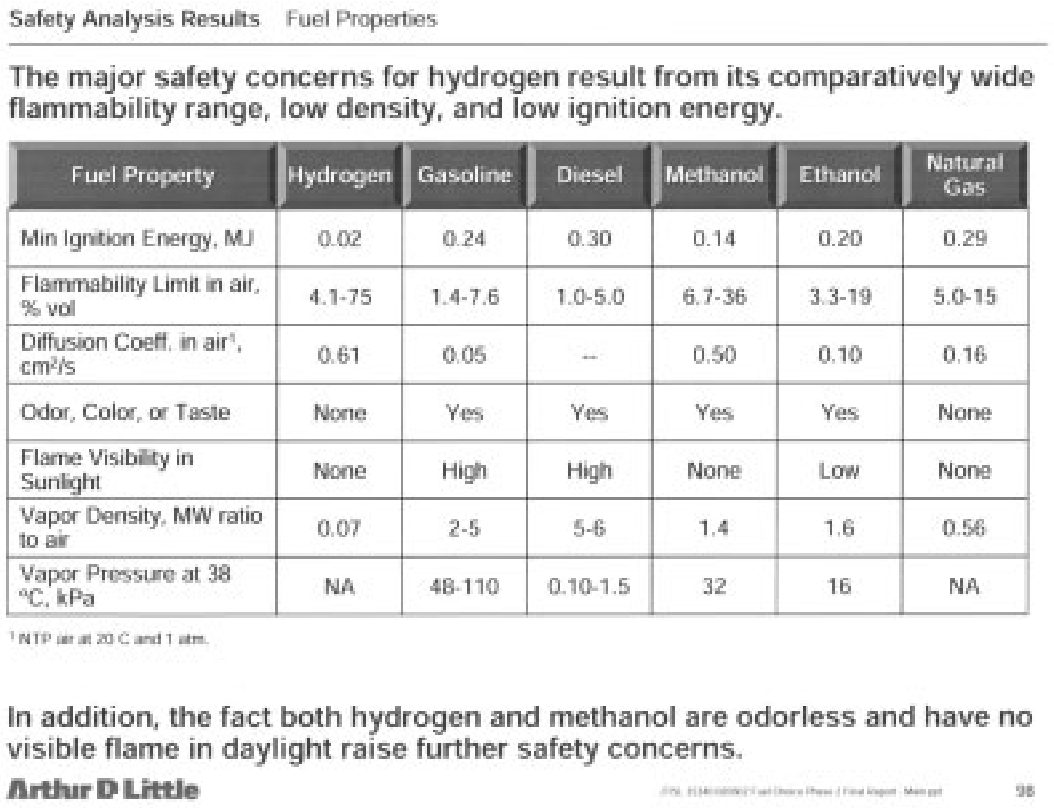
- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- Cost
- **Safety**
- Conclusion & DOE Target Setting



Although no fundamental technical barriers exist, meeting safety standards may pose a challenge for the implementation of hydrogen fuel chains.

- Hydrogen transportation, fueling station, and on-board safety issues can likely be resolved without onerous cost-increases
    - Relatively low cost engineering solutions can probably be identified for all issues surrounding on-board storage and refueling facilities for cH_2 and MH
    - However, the current codes and standards for the safe handling of hydrogen may not be practical for consumer applications
    - Well-organized international code and standard setting and modification are currently under way
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and on-road infrastructure that could be costly and difficult to implement
    - Fundamental safety-related properties of hydrogen are very different from gasoline
    - Implementation of critical safety measures for closed public structures may pose a serious hurdle to widespread use of cH_2, as responsibility for implementation does not easily align with interest in hydrogen as a fuel
    - This issue may necessitate alternative hydrogen storage methods (e.g. MH)
    - Insufficient attention is being paid to these issues by standard-setting efforts

A well-coordinated international effort is under way to tackle hydrogen safety issues, but it insufficiently addresses on-road issues.



Safety Analysis Results   Fuel Properties

The major safety concerns for hydrogen result from its comparatively wide flammability range, low density, and low ignition energy.

Fuel Property	Hydrogen	Gasoline	Diesel	Methanol	Ethanol	Natural Gas
Min Ignition Energy, MJ	0.02	0.24	0.30	0.14	0.20	0.29
Flammability Limit in air, % vol	4.1-75	1.4-7.6	1.0-5.0	6.7-36	3.3-19	5.0-15
Diffusion Coeff. in air[1], cm^2/s	0.61	0.05	--	0.50	0.10	0.16
Odor, Color, or Taste	None	Yes	Yes	Yes	Yes	None
Flame Visibility in Sunlight	None	High	High	None	Low	None
Vapor Density, MW ratio to air	0.07	2-5	5-6	1.4	1.6	0.56
Vapor Pressure at 38 °C, kPa	NA	48-110	0.10-1.5	32	16	NA

[1] NTP air at 20 C and 1 atm.

In addition, the fact both hydrogen and methanol are odorless and have no visible flame in daylight raise further safety concerns.

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Details on pages:
A104-111

The greatest combustion-related concern for hydrogen is a slow leak in a garage or enclosed area resulting in a fire or explosion.

Safety Variables of Concern	Negatives	Positives	Precautions
Flammability and Detonation	• Widest flammability range • Flammable at the high concentrations • More likely to detonate than other fuels	• Low volumetric energy density releases less energy during a leak, fire, or explosion • Flames are likely to be confined to a small area	• Ventilate enclosed areas or install miniature catalytic converters to eliminate hydrogen build-up • Prevent/detect leaks • Prevent entrance of air during fueling (collapsible storage vessels) • Install building and structural setbacks
Ignition Energy	• Very low ignition energy - common static (sliding over a car seat) is 10 times greater than minimum	• Ignition energy at the lower flammability limit is high (comparable to natural gas) • Conventional fuel cell temperatures (60-90° C) are too low for thermal ignition	• Use conductive fueling hoses • Wear NOMEX 11A static resistant protection while fueling • Use anti-static agents in fuel system components • Develop hydrogen compatible electrical products and use non-electrical devices when possible (e.g. hydraulic controls)

Details on pages:
A104-111

Potential leaks from high pressure storage systems have raised significant safety concerns.

Safety Variables of Concern	Negatives	Positives	Potential Actions
Gas and Flame Detection	• Asphyxiation from odorless and colorless gas • Burns from invisible flame	• Near-by people or object are less likely to get burned (low radiant heat transfer)	• Install UV/IR optical fire detection system • Develop fuel cell compatible odorant and flame visibility additive
Toxicity		• Hydrogen and its primary combustion product (water) are not toxic	• None required
High Pressure Storage	• High propensity to leak • Materials embrittlement • Rupture hazard • Damage from high pressure jet	• Unconfined leaks disperse quickly (high diffusion coefficient) • Current hydrogen designs project lifetimes of 15+ years at 3 cycles (refuelings) per day[1]	• Use 304 stainless to prevent embrittlement • Use X-ray welded seams to prevent leaks • Use break-away double shut-off fueling hoses • Install pressure relief and safety shut-off valves • Use ASME certified (or better), hydrostatically tested vessels • Thermal shock, corrosion, crash, high altitude, hot/cold weather tests

[1] Based on discussions with developers.

Details on pages:
A104-111

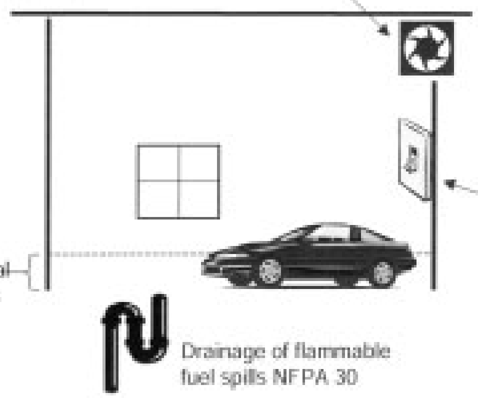
Cryogenic storage has most of the same safety concerns as compressed hydrogen, plus it can cause thermal damage.

Safety Variables of Concern	Negatives	Positives	Potential Actions
Cryogenic Storage	• Cold burns or frostbite from leaks/spills or un-insulated vessels or fuel lines • Combustion or asphyxiation from boil-off vapors/gases • Materials embrittlement • Rupture hazard	• Unconfined spills disperse quickly (high diffusion coefficient)	• Use 304 stainless to prevent embrittlement • Use break-away double shut-off transfer hoses • Install pressure relief and safety shut-off valves • Use ASME certified (or better), hydrostatically tested vessels • Thermal shock, corrosion, crash, high altitude, hot/cold weather tests • Rated insulation on all vessels, fuel lines, etc.

Metal hydrides are the safest storage option due to the high energy requirement for hydrogen release.

Details on pages: A113-114

Even conventional and alternative liquid fueled vehicles require several facility safety design considerations.



Elimination of ignition sources - smoking,cutting, welding, static, hot surfaces NFPA 30, 70, 77, 78

Air Circulation
NFPA 30, 88A, 88B

NFPA 70 Electrical Standards

Class 1, Div 2 only electrical equipment within 18 inches of floor NFPA70

Drainage of flammable fuel spills NFPA 30

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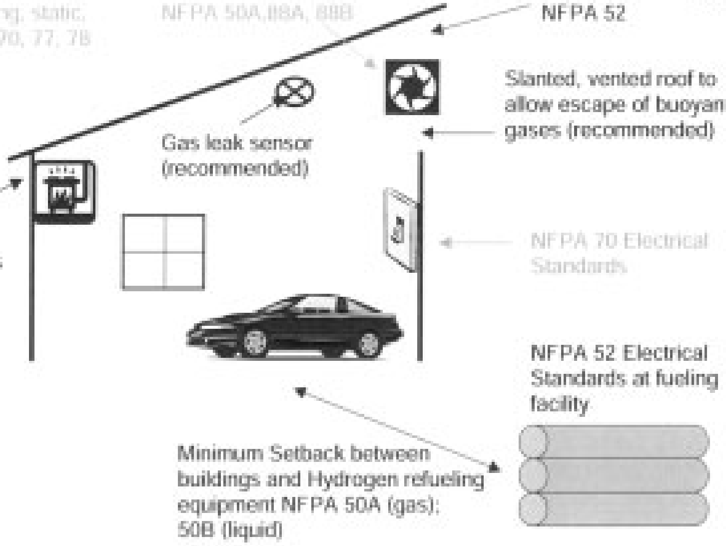
Details on pages:
A113-114

Safety Analysis Results Facility Design Considerations *Hydrogen*

Additional design considerations must be made for hydrogen vehicles, some of which could be very expensive in certain cases.



Elimination of ignition sources - smoking,cutting, welding, static, hot surfaces – NFPA 70, 77, 78

Air Circulation
NFPA 50A,88A, 88B

Explosion Venting
NFPA 52

Slanted, vented roof to allow escape of buoyant gases (recommended)

Gas leak sensor (recommended)

No open flame heaters
NFPA 50A

NFPA 70 Electrical Standards

NFPA 52 Electrical Standards at fueling facility

Minimum Setback between buildings and Hydrogen refueling equipment NFPA 50A (gas); 50B (liquid)

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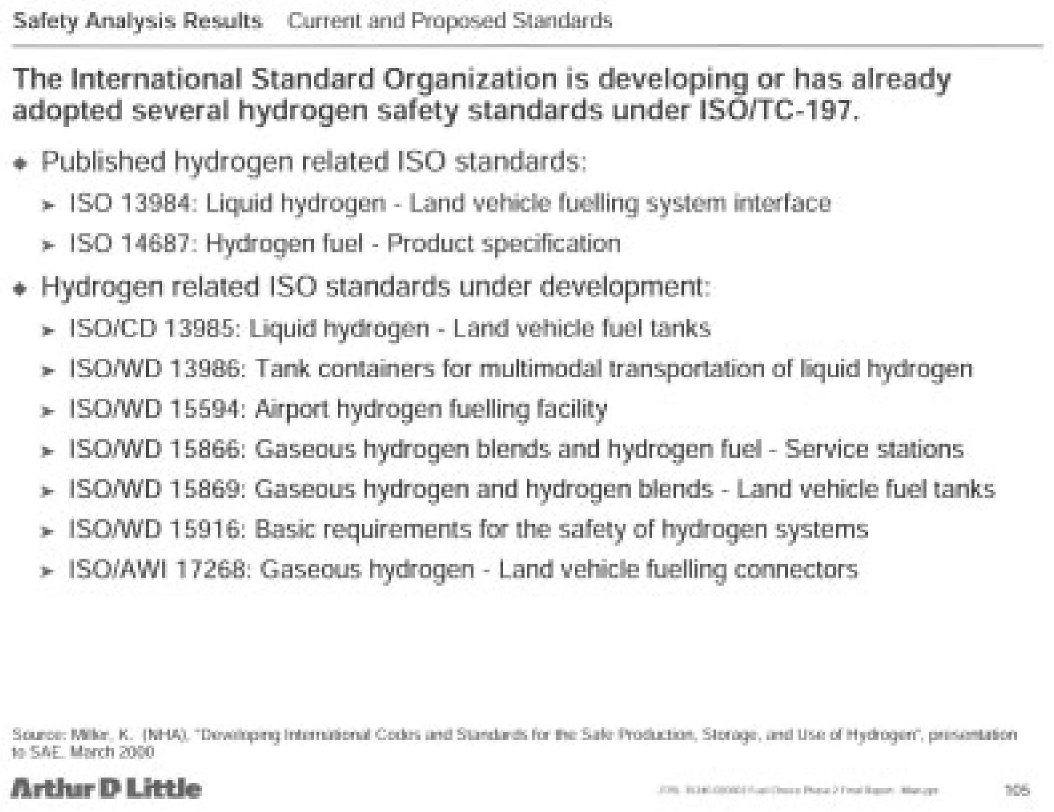
Details on pages:
A112

Many organizations are responsible for or are working on hydrogen related safety standards.

- Guidelines for storage systems
  - National Fire Protection Association (NFPA)
- Regulations for hydrogen distribution over the roadways
  - Department of Transportation (DOT)
- Standards for hydrogen equipment
  - American National Standards Institute (ANSI)
  - American Society of Mechanical Engineers (ASME)
- Standards for gas production, handling, and use (including hydrogen)
  - Compressed Gas Association (CGA)
- Standards for fuel cell safety and interface
  - International Electrotechnical Commission (IEC)
- Standards for alternative automotive fuel systems
  - Society of Automotive Engineers (SAE)
- General Standards Organizations
  - American National Standards Institute (ANSI)
  - International Standards Organization (ISO)
  - International Codes Council (ICC)

Most of these categories overlap in one way or another.



Safety Analysis Results Current and Proposed Standards

The International Standard Organization is developing or has already adopted several hydrogen safety standards under ISO/TC-197.

- Published hydrogen related ISO standards:
  - ISO 13984: Liquid hydrogen - Land vehicle fuelling system interface
  - ISO 14687: Hydrogen fuel - Product specification
- Hydrogen related ISO standards under development:
  - ISO/CD 13985: Liquid hydrogen - Land vehicle fuel tanks
  - ISO/WD 13986: Tank containers for multimodal transportation of liquid hydrogen
  - ISO/WD 15594: Airport hydrogen fuelling facility
  - ISO/WD 15866: Gaseous hydrogen blends and hydrogen fuel - Service stations
  - ISO/WD 15869: Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks
  - ISO/WD 15916: Basic requirements for the safety of hydrogen systems
  - ISO/AWI 17268: Gaseous hydrogen - Land vehicle fuelling connectors

Source: Miller, K. (NHA), "Developing International Codes and Standards for the Safe Production, Storage, and Use of Hydrogen", presentation to SAE, March 2000

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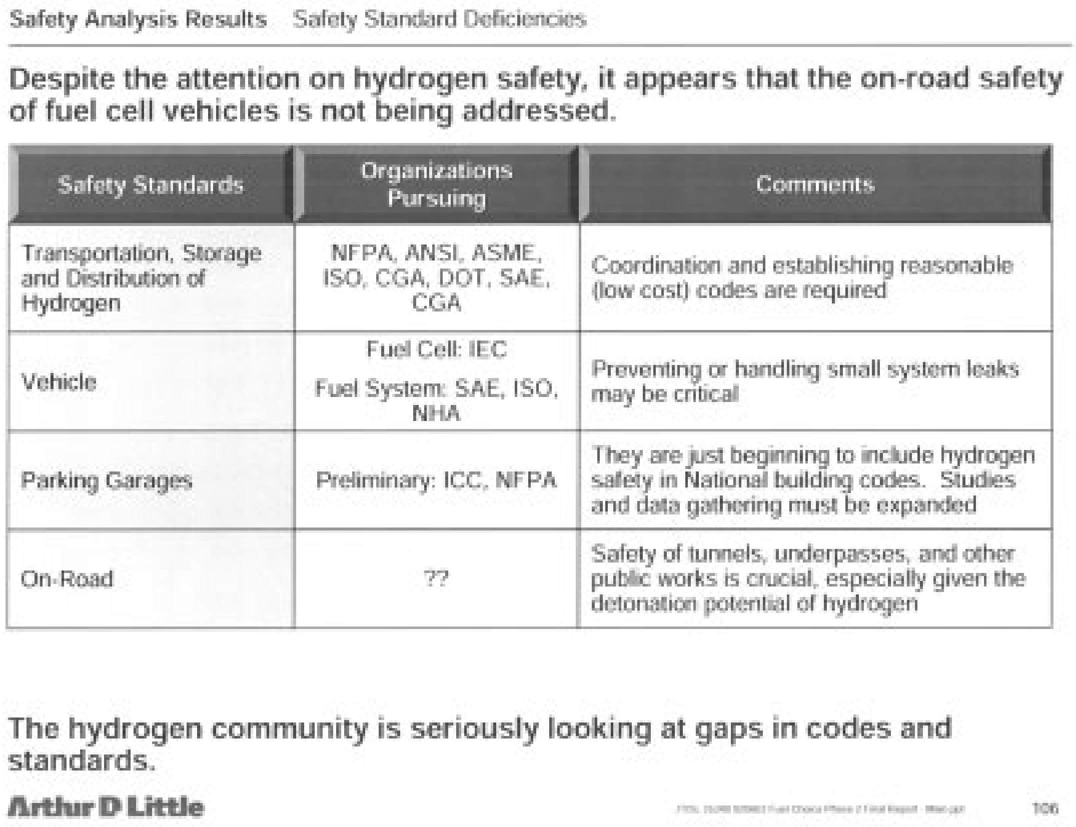
105



Safety Analysis Results   Safety Standard Deficiencies

Despite the attention on hydrogen safety, it appears that the on-road safety of fuel cell vehicles is not being addressed.

Safety Standards	Organizations Pursuing	Comments
Transportation, Storage and Distribution of Hydrogen	NFPA, ANSI, ASME, ISO, CGA, DOT, SAE, CGA	Coordination and establishing reasonable (low cost) codes are required
Vehicle	Fuel Cell: IEC Fuel System: SAE, ISO, NHA	Preventing or handling small system leaks may be critical
Parking Garages	Preliminary: ICC, NFPA	They are just beginning to include hydrogen safety in National building codes. Studies and data gathering must be expanded
On-Road	??	Safety of tunnels, underpasses, and other public works is crucial, especially given the detonation potential of hydrogen

The hydrogen community is seriously looking at gaps in codes and standards.

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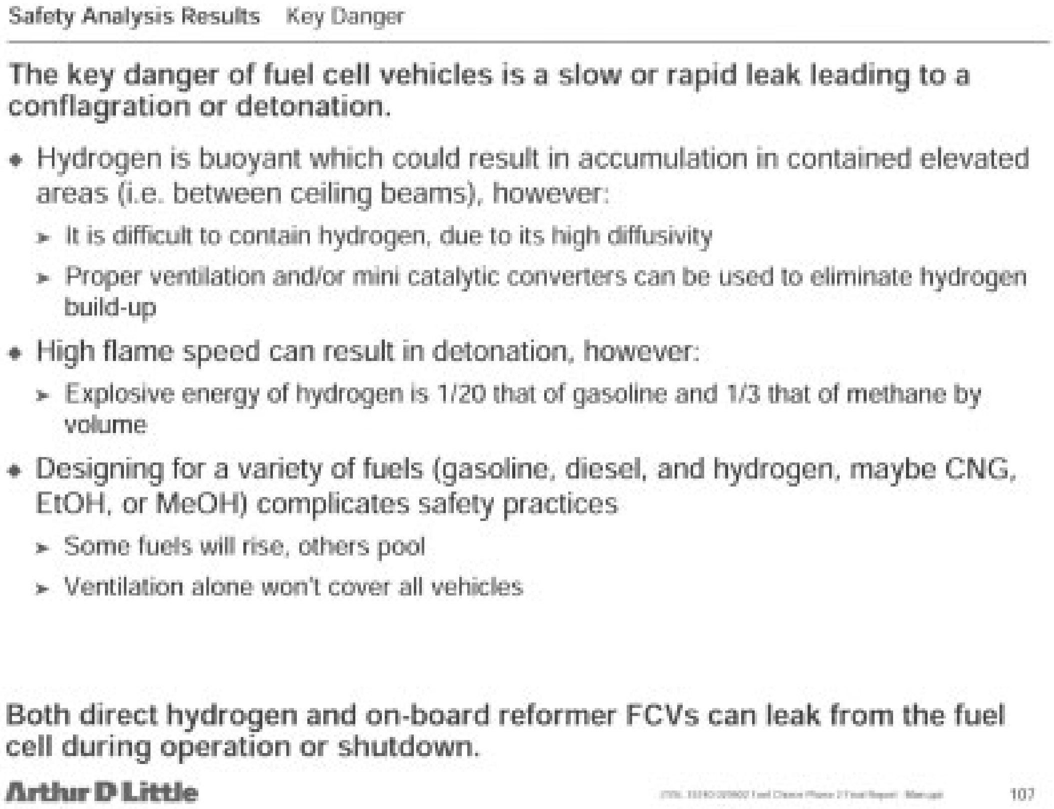


The key danger of fuel cell vehicles is a slow or rapid leak leading to a conflagration or detonation.

- Hydrogen is buoyant which could result in accumulation in contained elevated areas (i.e. between ceiling beams), however:
  - It is difficult to contain hydrogen, due to its high diffusivity
  - Proper ventilation and/or mini catalytic converters can be used to eliminate hydrogen build-up
- High flame speed can result in detonation, however:
  - Explosive energy of hydrogen is 1/20 that of gasoline and 1/3 that of methane by volume
- Designing for a variety of fuels (gasoline, diesel, and hydrogen, maybe CNG, EtOH, or MeOH) complicates safety practices
  - Some fuels will rise, others pool
  - Ventilation alone won't cover all vehicles

Both direct hydrogen and on-board reformer FCVs can leak from the fuel cell during operation or shutdown.

There are some important areas that must be addressed before FCVs can be accepted as mass market vehicles.

- Key Uncertainties: home parking, maintenance facilities, and parking garages
  - Some studies and modeling has been conducted, but data gathering must be expanded
    - Ventilation and leak modeling at the University of Miami has been funded for several years
  - Elevated vents may be enough in most cases, but it must be done for all places the vehicle visits or there could be major consequences
    - Prohibiting FCVs in non-compliant areas may result in unreasonable inconvenience to FCV owner
    - FCV owners and manufacturers won't have a great deal of leverage to force these facilities to be hydrogen compliant
- Potential Show Stoppers: tunnels and other public road works
  - Safety equipment will have to be very cheap or the aggregate cost could be prohibitive
  - All roads must be compliant - keeping certain cars off a particular road would be extremely difficult and unacceptable to the FCV owner

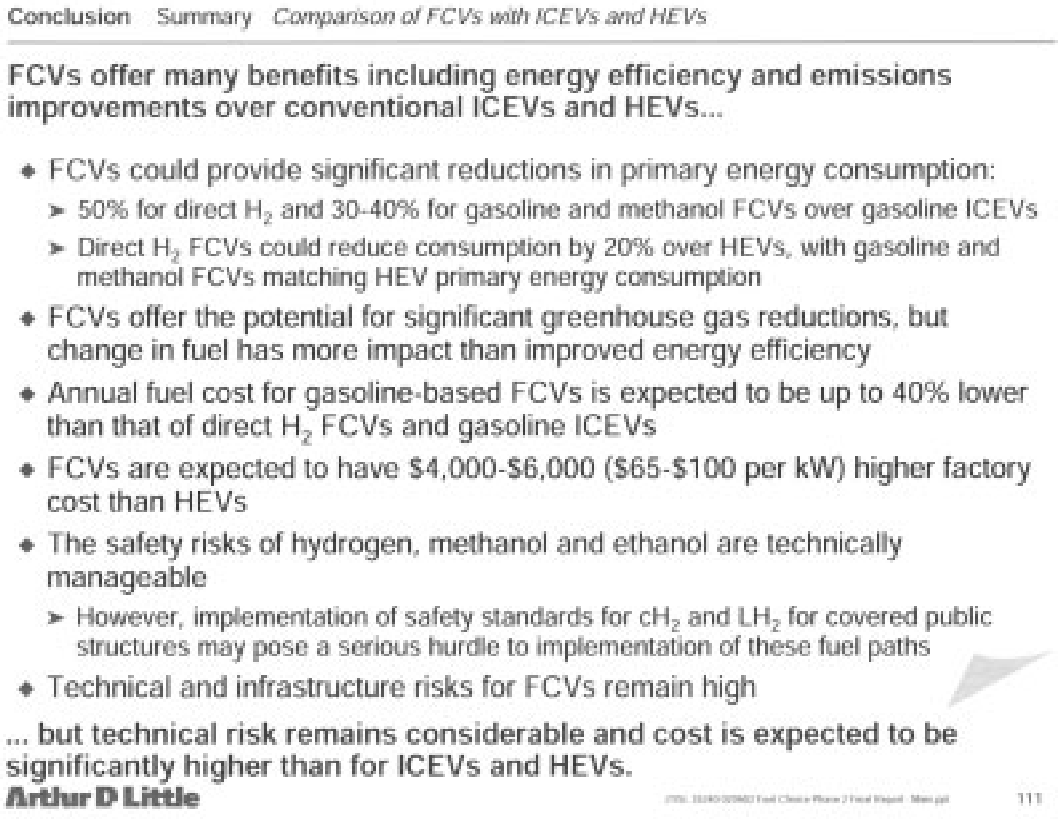
Outline

Main Report

- Background, Objectives & Scope
- Approach
- Energy Efficiency and Emissions
- Cost
- Safety
- **Conclusion & DOE Target Setting**

Hydrogen FCVs should be able to significantly reduce energy use and greenhouse gas emissions, but at much higher cost.

- Based on our analysis, hydrogen FCVs could achieve 2.5 MJ/mi energy use and 150 g/mi greenhouse gas emissions on a well-to-wheels basis
  - 50-60% improvement over gasoline ICEVs
  - Requires compressed gas hydrogen production (central or local) from natural gas
  - Requires hydrogen FCVs to achieve 2.5x fuel economy improvement (80 mpgge) over gasoline ICEVs
- However, we estimate this hydrogen FCV to cost more than $5,000 per year for vehicle depreciation, fuel, and maintenance
  - Lowest among FCV options, but still $1,000/year more than HEVs and $1,500/year more than a gasoline ICEV
  - Hydrogen cost is not a major contributor, but this analysis indicates a target of $20/GJ should be achievable in the long-term
  - The estimated hydrogen FCV factory cost of $16,000 is $4,000 higher than HEVs and $5,000 higher than a gasoline ICEV due to higher FCV powertrain costs
- Our safety issues analysis indicates that more attention needs to be paid to covered public structure compatibility with hydrogen



Conclusion Summary *Comparison of FCVs with ICEVs and HEVs*

FCVs offer many benefits including energy efficiency and emissions improvements over conventional ICEVs and HEVs...

- FCVs could provide significant reductions in primary energy consumption:
  - 50% for direct H_2 and 30-40% for gasoline and methanol FCVs over gasoline ICEVs
  - Direct H_2 FCVs could reduce consumption by 20% over HEVs, with gasoline and methanol FCVs matching HEV primary energy consumption
- FCVs offer the potential for significant greenhouse gas reductions, but change in fuel has more impact than improved energy efficiency
- Annual fuel cost for gasoline-based FCVs is expected to be up to 40% lower than that of direct H_2 FCVs and gasoline ICEVs
- FCVs are expected to have $4,000-$6,000 ($65-$100 per kW) higher factory cost than HEVs
- The safety risks of hydrogen, methanol and ethanol are technically manageable
  - However, implementation of safety standards for cH_2 and LH_2 for covered public structures may pose a serious hurdle to implementation of these fuel paths
- Technical and infrastructure risks for FCVs remain high

... but technical risk remains considerable and cost is expected to be significantly higher than for ICEVs and HEVs.

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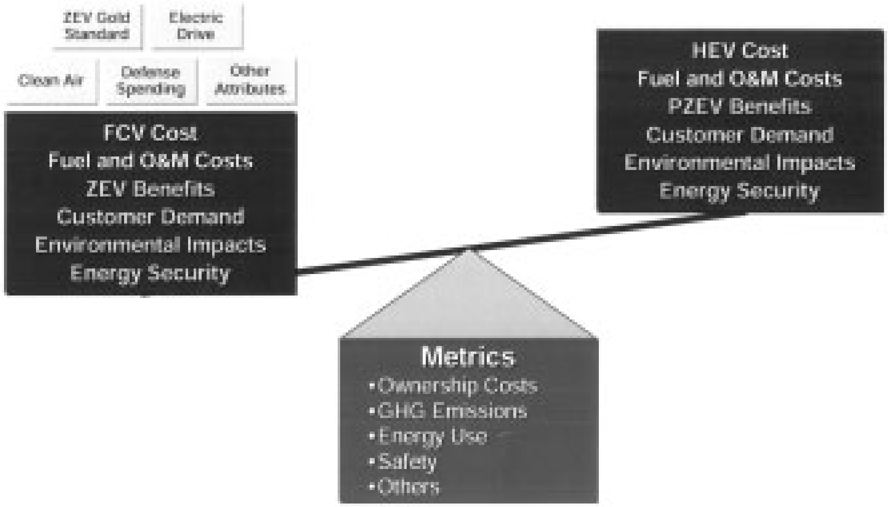
Although there are considerable differences in performance, risk, and cost of the FCV fueling options, no clear winner is identifiable.

- Compressed hydrogen FCVs could have significant benefits over reformer-based vehicles
  - ➢ 20-30% lower primary energy consumption than gasoline or methanol FCVs
  - ➢ \$1,000-\$2,000 (\$15-\$35 per kW) lower cost per vehicle; this could be increased to around around \$3,500 (\$60/kW) if some efficiency benefit is sacrificed
  - ➢ Significantly lower technical risk
- Reformer-based systems retain considerable benefits in terms of infrastructure risk
  - ➢ Delivered fuel costs are likely to be less than half that of hydrogen on a \$/GJ basis
  - ➢ Even infrastructure investment for methanol is very modest compared to hydrogen
  - ➢ Safety issues for reformer fuels are comparatively simple to resolve, despite recent public perception of methanol's toxicity risk
- Differences between FCVs and petroleum ICEVs overwhelm differences amongst FCV options
- Hydrogen ICEVs do not appear to offer significant benefits in typical ownership cost compared with direct hydrogen FCVs
  - ➢ cH_2 ICEV range is likely to be reduced due to the large volume of hydrogen required

Details on pages:
A121-123

DOE Target Setting Comparing Cost *A Level Playing Field*

Our analysis shows that FCVs ownership costs will be high, but all attributes of vehicle operation are not taken into account.



ZEV Gold Standard

Electric Drive

Clean Air

Defense Spending

Other Attributes

FCV Cost
Fuel and O&M Costs
ZEV Benefits
Customer Demand
Environmental Impacts
Energy Security

HEV Cost
Fuel and O&M Costs
PZEV Benefits
Customer Demand
Environmental Impacts
Energy Security

Metrics

- Ownership Costs
- GHG Emissions
- Energy Use
- Safety
- Others

Details on pages: A124-125

Minimum allowable cost for FCVs should be similar to advanced HEV powertrains with additional emissions control.

- Based on our "round-robin" analysis, HEV powertrain cost would be around $4,000 for gasoline HEVs and $5,000 for diesel HEVs
  - Compared with around $3,500 for a conventional powertrain
  - Gasoline HEVs would have higher well-to-wheels energy use than gasoline FCVs
  - Both would have higher emissions than gasoline FCVs
- ICE additional costs to meet PZEV emission regulations would increase gasoline HEV cost by another $500-$1,500
  - Based on "round-robin" analysis
  - Direct hydrogen FCVs provide emission reductions beyond PZEV
- Round-robin analysis may not accurately reflect projections of manufacturers:
  - Some current HEV manufacturers indicate that our HEV projections are not realistic
  - Round-robin assessment for FCVs would have likely led to lower cost estimate than projected here
  - However, HEVs are technically almost production-ready
- Not taking into account the accuracy of round-robin analyses, **minimum mid-sized vehicle powertrain targets should be around $5,000 per vehicle**
  - Our detailed analysis indicates a hydrogen FCV powertrain cost of $9,000

The detailed analysis described in this study generally supports the targets defined in Phase I, ...

- Well-to-wheel energy efficiency projections based on our scenarios are generally consistent with the long-term (2008) targets suggested in Phase I
- Phase I hydrogen fuel cost targets appear difficult to achieve and the DOE should consider relaxing them
  - Given the modest impact of fuel cost on overall ownership cost
- None of the FCV future scenarios met DOE FCV cost targets of $45 per kW
- Given the performance benefits of FCVs, relaxing the target to match the cost of HEVs meeting the PZEV standard may be reasonable

... but indicates that hydrogen and FCV cost targets may be difficult to achieve without additional technology breakthroughs.

Table of Contents

Appendix Table of Contents

Outline

Appendix

- **Glossary**
- Fuel Chain Analysis Assumptions
- Vehicle Analysis Assumptions
- Platinum Loading Modeling
- Additional Analysis Results
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- Target Setting
- Bibliography

Appendix Glossary

ADL	Arthur D. Little, Inc.
ANL	Argonne National Lab
BOP	Balance of Plant
CEM	Compressor/Expander Module
cH_2	Compressed Hydrogen (gaseous)
CNG	Compressed Natural Gas
DOE	Department of Energy (United States)
E100	Ethanol (100%)
EV	Electric Vehicle
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas (CO_2, CH_4, etc.)
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (model developed by ANL)
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LH_2	Liquid Hydrogen
Li Ion	Lithium Ion Battery
MeOH	Methanol
mpgge	Miles per Gallon Gasoline Equivalent
NG	Natural Gas
NHA	National Hydrogen Association
NiMH	Nickel Metal Hydride Battery
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OTT	Office of Transportation Technologies
Pb Ac	Lead Acid Battery
PEMFC	Polymer Electrolyte Membrane Fuel Cell
R&D	Research and Development
RFG	Reformulated Gasoline
SAE	Society of Automotive Engineers
scfd	Standard Cubic Feet per Day
SR	Steam Reformer
V	Volts

Liquid and Gaseous Fuel Specifications

Fuel[1]	Formula/State	C	H	O	H/C	MW	Density [1] (kg/m³)	HHV (MJ/kg)	LHV (MJ/kg)
Diesel No. 2	$C_{12.4}H_{21.15}$ (l)	12.4	21.15	0	1.706	170.25	863	46.5	42.6
Gasoline	$C_{6.55}H_{13.26}$ (l)	6.55	13.26	0	2.024	92.03	719	48.4	44.7
RFG	$C_{6.69}H_{13.65}O_{0.121}$ (l)	6.69	13.65	0.12109	2.041	96.05	719	47.2	43.7
Natural Gas	$CH_{3.85}O_{0.019}N_{0.031}$ (g)	1	3.85	0.0192	3.85	16.63	0.81	52.34	47.22
CNG	(g) 245 bar						201.3		
Ethanol	C_2H_5OH (l)	2	6	1	3	46.07	785	29.8	27.0
Methanol	CH_3OH (l)	1	4.00	1	4	32.04	792	22.8	20.0
Hydrogen	H_2 (g)	0	2	0	--	2.02	0.098	142.1	119.9
cH2	(g) 340 bar						24.7		
LH2	(l) 1.58 bar, 22K						68.7		

Reference: Lindeburg '94, CRC Handbook of Chemistry and Physics '87, Gieck '89, Kanury & Unnasch, 1996, Heywood, 1988.

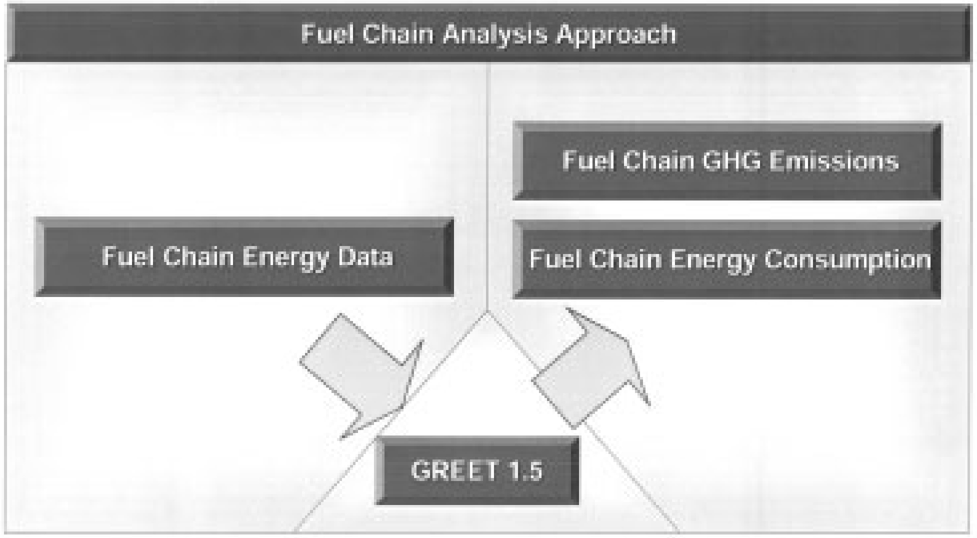
[1] Density for gaseous fuels are at 1 atm, 25 C.

Outline

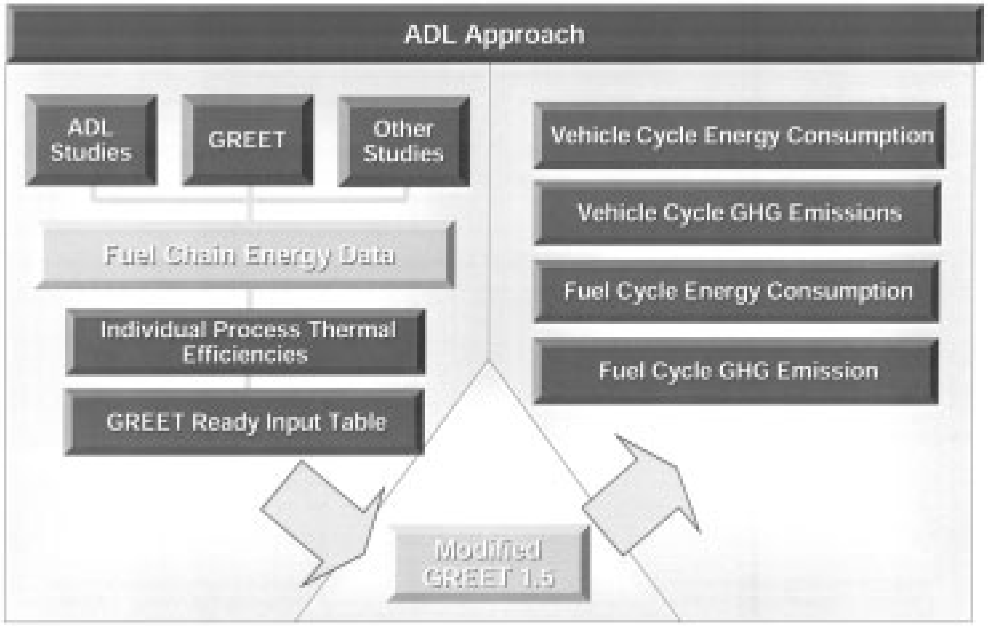
Energy efficiency inputs for the fuel chains were confirmed with process modeling and industry experience.

- Efficiency inputs for all fuel chain steps are documented
  - Data are represented in units that relate to referenced information
  - Values are converted to LHV efficiencies as input to GREET
- All compression associated with on-site hydrogen production is done with electric grid power assuming a U.S. average mix
- Liquification and compression associated with central hydrogen production is done with a 50/50 mix of electric grid and NG ICEs
- No credits for steam production for remote methanol plants
- Corn stover is feedstock for cellulosic biomass-to-ethanol facilities
- U.S. power generation mix is the baseline for EV power
  - Emissions & efficiency is weighted average of all sources

We updated Argonne National Lab's GREET Model with knowledge from our fuel chain database to provide a transparent and referable description of fuel chain options.



ADL modified the typical GREET approach to accommodate new fuel-choice options and obtain sub-level information.



ADL Approach

ADL Studies

GREET

Other Studies

Fuel Chain Energy Data

Individual Process Thermal Efficiencies

GREET Ready Input Table

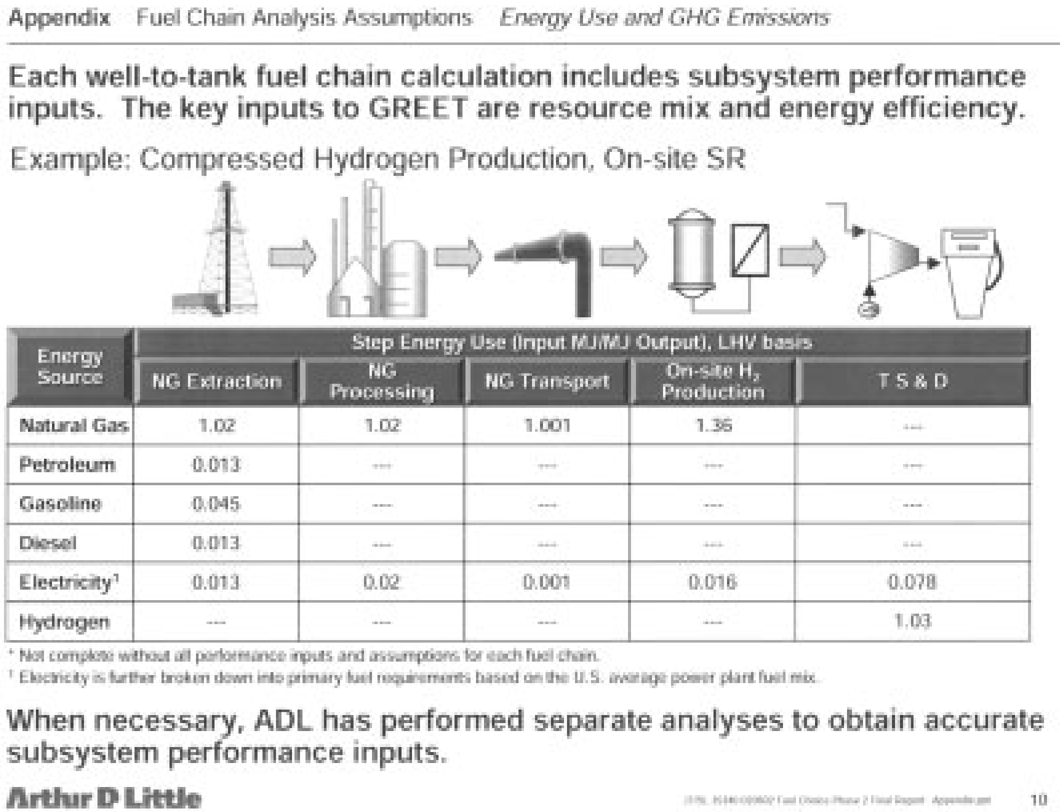
Modified GREET 1.5

Vehicle Cycle Energy Consumption

Vehicle Cycle GHG Emissions

Fuel Cycle Energy Consumption

Fuel Cycle GHG Emission



Each well-to-tank fuel chain calculation includes subsystem performance inputs. The key inputs to GREET are resource mix and energy efficiency.

Example: Compressed Hydrogen Production, On-site SR

Energy Source	Step Energy Use (Input MJ/MJ Output), LHV basis				
	NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
Natural Gas	1.02	1.02	1.001	1.36	---
Petroleum	0.013	---	---	---	---
Gasoline	0.045	---	---	---	---
Diesel	0.013	---	---	---	---
Electricity[1]	0.013	0.02	0.001	0.016	0.078
Hydrogen	---	---	---	---	1.03

* Not complete without all performance inputs and assumptions for each fuel chain.

[1] Electricity is further broken down into primary fuel requirements based on the U.S. average power plant fuel mix.

When necessary, ADL has performed separate analyses to obtain accurate subsystem performance inputs.

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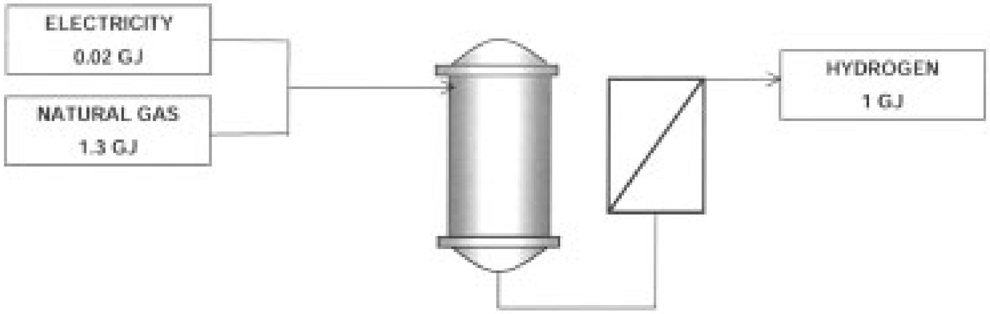
We have defined the primary performance input for each module so that stage efficiency can be calculated on a LHV basis as an input to GREET.

Example: Compressed Hydrogen Production, On-site SR



ELECTRICITY
0.02 GJ

NATURAL GAS
1.3 GJ

HYDROGEN
1 GJ

Module Efficiency = Energy Output/ Energy Input

ME = 1/1.32 = 75.6%

We documented the calculations and data sources for each step in the fuel chain in production and transportation modules.

Production and Fuel Processing	
P1	Natural Gas Extraction
P2	Natural Gas Processing
P3	Hydrogen On-site Production & Compression
P4a	Hydrogen Central Production
P4b	Hydrogen On-site Compression, Tube-Trailer
P5	Hydrogen On-site Compression, Pipeline
P6	Hydrogen Central Liquefaction
P7	Hydrogen On-site Electrolysis
P8	Metal Hydride On-site Production & Compression
P9	Natural Gas Compression
P10	Petroleum Extraction
P11	Petroleum Refining to Gasoline
P12	Methanol from Natural Gas
P13	Corn Farming
P14	Ethanol from Corn
P15	Petroleum Refining to Diesel
P16	Biomass Chipping
P17	Biomass to Ethanol
P18	Corn Stover Collection
P19	Ethanol from Corn Stover
P20	Electricity Generation

Feedstock and Fuel Transport	
T1	Natural Gas Pipeline
T2	Hydrogen Pipeline
T3	Liquid Hydrogen Transport
T4	Hydrogen Tube Trailer
T5	Petroleum Transport
T6	Gasoline Truck
T7	Methanol Truck
T8	Methanol Marine Transport
T9	Corn Truck
T10	Ethanol Marine
T11	Ethanol Truck
T12	Ethanol Train
T13	Diesel Truck
T14	Biomass Truck
T15	Power Transmission

Note: Detailed fuel chain data and efficiency calculations are found in the Appendix Supplement

We assured that consistent assumptions were used for different fuels throughout the fuel chain.

Complete fuel chains are constructed from a combination of the modules.

Fuel Chain	Fuel Chain Module				
	Extraction	Processing	Transport	Production	T S & D
RFG, Petroleum	P10	--	T5	P11	T6
Diesel, Petroleum	P10	--	T5	P15	T13
Methanol, NG	P1	P2	T1	P12	T8, T7
Ethanol, Corn Stover	P18	T14	T10, T12	P19	T11
Ethanol, Corn	P13	T9	T10, T12	P14	T11
cH2, On-site NG SR	P1	P2	T1	P3	---
cH2, On-site NG SR, Energy Station	P1	P2	T1	P3	---
cH2, On-site NG SR, MH	P1	P2	T1	P3	P8
cH2, Central NG, Tube Trailer	P1	P2	T1	P4a,b	T4
cH2, Central NG, Pipeline	P1	P2	T1	P4a	T2,P5
cH2, Central NG, LH2	P1	P2	T1	P4a,P6	T3
cH2, On-site Electrolyzer	P20		T15	P7	--

Fuel cost assumptions were based on EIA energy projections, ADL experience with fuel production, and detailed modeling of local hydrogen fueling stations.

- Transportation and distribution costs are based on literature and ADL experience with fueling facility installations
- Gasoline and diesel wholesale prices are based EIA projections for crude oil and historical price spreads between petroleum products and crude oil
- Methanol and ethanol wholesale prices are based on ADL projections and cost analysis of production facilities
- Costs of hydrogen are based on bottom-up cost analysis
  - Local hydrogen fueling station capital costs are based on vendor quotes and central plant capital costs are based on published and internal data
  - All compression associated with on-site hydrogen production from natural gas is done with electric grid power at $0.07/kWh (EIA projected 2010 commercial rate)
  - On-site hydrogen production from electrolysis assumes 0.07, 0.08, 0.09 and 0.04 $/kWh for U.S. mix, nuclear, wind, and nighttime power, respectively
    - Nighttime power electrolysis option includes additional storage and hydrogen generation capacity to operate for only 12 hours a day

For non-hydrogen alternative fuels, bottom-up analyses from previous Arthur D. Little studies were used.

- Methanol wholesale costs relied on extensive GTL analyses performed for a range of studies vetted by several key methanol industry players
  - Whole sale price of $120/tonne including transportation to the local fueling station
    - Approximately the same price as RFG since refineries can use methanol as MTBE
- Ethanol costs are based on a previous ADL Biomass study (ADL, 2001) and *The USDA 1998 US Ethanol Cost of Production Survey* (Shapouri, 1999) for corn ethanol
  - This study assumed a future projected wholesale price of $1.10/gal
  - USDA Survey estimated $1.12/gal wholesale
    - Existing plants ranging from 1-50 million gal/year, both wet and dry mills
  - ADL Biomass study estimated $1.29 wholesale
    - Greenfield plant, dry mill
    - Assuming corn price of $2.90/dry bushel and DDS price of $0.151/kg based on 1996-1998 regional corn prices across the U.S.
- Transportation and local fueling station costs are consistent with gasoline, but higher on a $/MJ basis due to lower volumetric energy density

Local hydrogen fueling station capital costs are based on vendor quotes and central plant capital costs are based on published and internal data.

- Local capital costs are based on detailed thermodynamic modeling and vendor quotes for components
  - 300 hydrogen vehicle per day fueling stations
    - integrated into existing gasoline station serving 600 vehicles per day total
    - 90% capacity factor
  - 100 units per year production volume for all components
  - Appropriate scaling factors and progress ratios were applied
  - 11% Capital Recovery factor[1]
  - Maintenance cost 5% of capital
- Central plant capital costs are based on published and internal data
  - 300 ton per day plant
  - 17% Capital Recovery factor[1]

[1] Differences in financial assumptions reflect typical differences in capital productivity expectations in different parts of the value chain.

We estimated electricity costs from renewable and nuclear power for use in on-site electrolyzers.

- Cost assumptions for power generation are in keeping with respective industry expectations

Power Cost, $/kWh	CR Factor[1]	Capacity Factor[1]	Capital Costs	Operating Costs	T&D and Other Costs	Selling Price
Fossil Fuel CCGT for comparison	15%	65%	0.014	0.010	0.045	0.069
Solar (PV)	15%	21%	0.822	0.001	0.040	0.863
Wind (nighttime)	15%	33%	0.051	0.001	0.040	0.092(0.04)
Nuclear	9%	75%	0.027	0.010	0.045	0.082

  - Solar power is too expensive to be used for large scale hydrogen generation based on the capital cost assumptions used here
  - Nuclear and wind power could be 50% more expensive than grid power, but are essentially emission free
    - Contracts for nighttime purchases would be less costly
- While hydro-power is a relatively cheap and reliable source of renewable power, we did not include it in this analysis under the assumption that there would be no significant additional capacity in the U.S.

[1] CR = Capital Recovery Factor, Capacity Factor = hours/year

The detailed hydrogen cost analysis of on-site SR production performed in this Phase provided refinements to the cost estimates of Phase I.

- Phase I estimates used available performance and cost information
  - 15% Capital Recovery factor, maintenance cost 10% of capital
  - $0.05/kWh for power and $3/MMBtu (HHV) for natural gas
  - did not include site prep and controls
  - detailed analysis was not performed
- This analysis was based on detailed thermodynamic modeling and vendor quotes for components
  - 11% Capital Recovery factor, maintenance cost 5% or capital
  - $0.07/kWh for power and $5/MMBtu (HHV) for natural gas based on EIA projected 2010 commercial rates

Hydrogen processing and purification performance assumptions for Phase II were generally consistent with the ranges used in Phase I.

Local NG SR with PSA	Units	Phase I Analysis	Phase II Analysis
Processing scale	SCFD Hydrogen	$<1 \times 10^6$	275,000
SR pressure	atm	5-20	10
SR methane slip	%	5-6	9
Burner air compressor efficiency	%	NA	70
PSA inlet / outlet pressure	atm	10-55	10 / 9
PSA hydrogen recovery	%	75-90	76
Fan / pump efficiency	%	NA	55 / 80
Overall LHV efficiency (SMR+PSA)[1]	%	65-75	74

[1] Inefficiencies in the PSA (unburned hydrogen) are used in the SR to increase overall efficiency. Assumes 33% and 35% power plant efficiency penalty on power requirements for Phase I and Phase II, respectively.

Hydrogen compression, on-site storage, and dispensing performance assumptions for Phase II were also very similar to Phase I.

Local Compression, Storage & Dispensing	Units	Phase I Analysis	Phase II Analysis
Compressor adiabatic efficiency	%	65-75	70 and 90 [1]
Compressor parasitics[2]	%	15-25	18
Storage pressure[3]	atm	250-350	240
Storage efficiency	%	~100	100
Chiller COP[4]		NA	3.5

[1] 3-stage rotary compressor used to pressurize hydrogen from the PSA outlet to the on-site storage tanks (at 3500 psi) is assumed to be 70% efficient. The two accumulator type compressors used to fuel the vehicle are assumed to be 90% efficient.

[2] Percent of output hydrogen. Assumes 33% and 35% power plant efficiency penalty on power requirements for Phase I and Phase II, respectively.

[3] For on-site pressurized tank storage from NG SR with PSA.

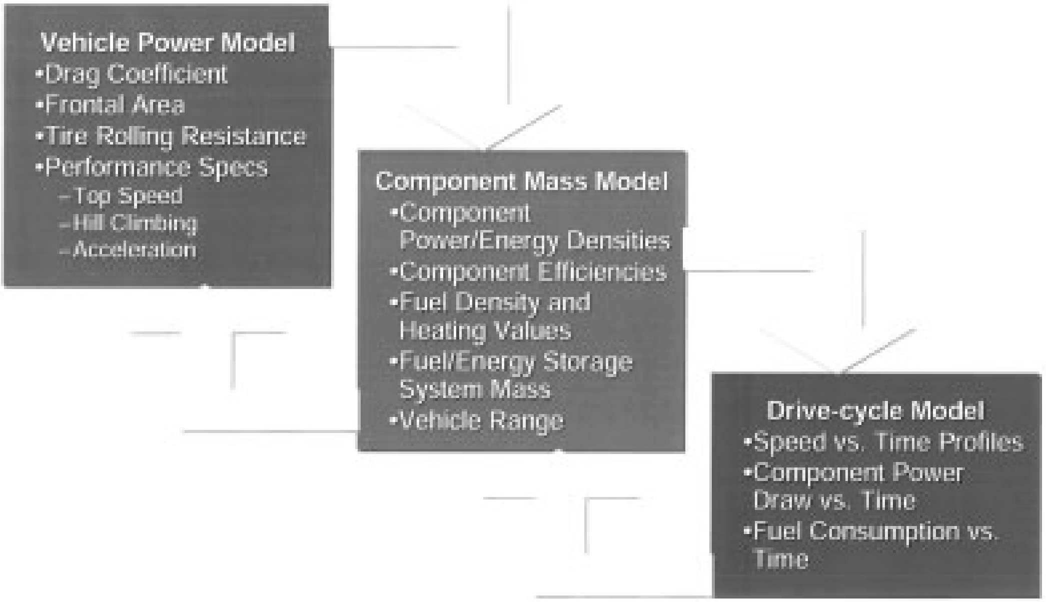
[4] We assume a chiller will be required to sub-cool the hydrogen entering the vehicle tank to prevent under-filling due to compression heating.

Outline

Appendix

- Glossary
- Fuel Chain Analysis Assumptions
- **Vehicle Analysis Assumptions**
- Platinum Loading Modeling
- Additional Analysis Results
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- Target Setting
- Bibliography

We used a vehicle drive-cycle simulation model to estimate fuel economy and to estimate the power requirements for each powertrain.



Vehicle Power Model

- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model

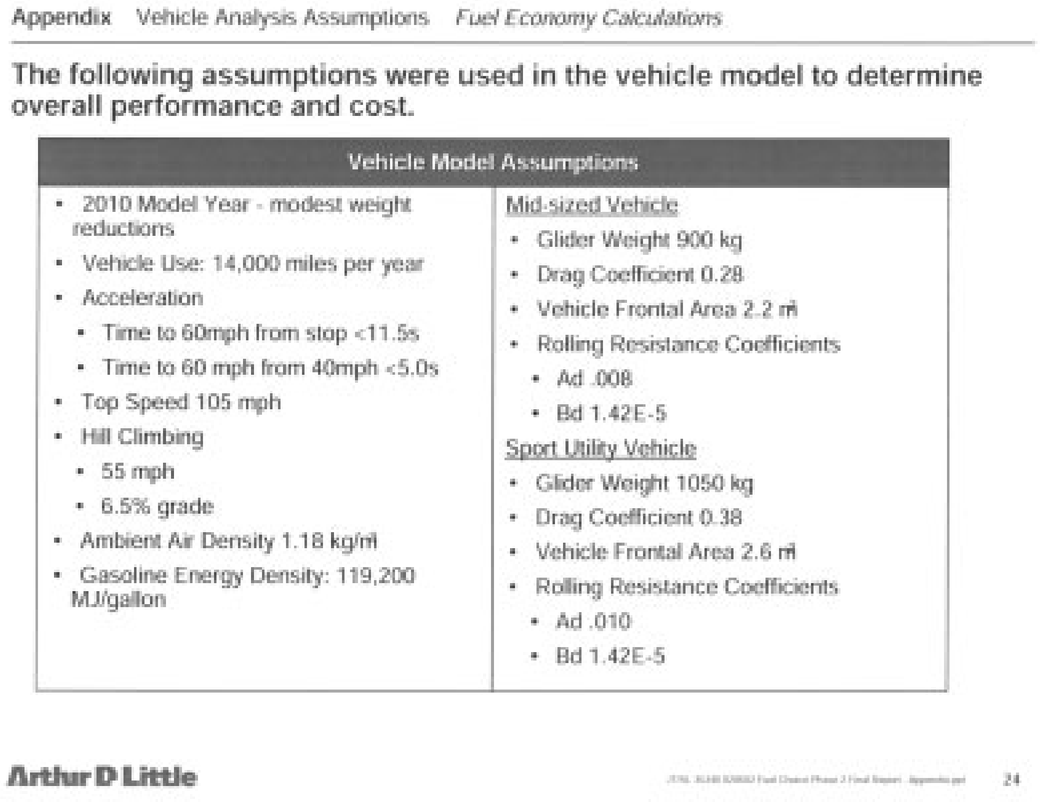
- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

Drive-cycle Model

- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

Key assumptions for vehicle performance and cost analysis:

- Vehicle mass and cost analysis based on previous and on-going ADL analyses
  - FCV power unit mass and cost based on on-going ADL/DOE analysis of automotive fuel cell systems (DE-SCO2-98EE50526)
  - Motor, transmission, battery, and other components based on ADL/EPRI HEV study (EPRI 2001)
  - Fuel cell and ICE engine costs are scaled with road power demand
  - Road power demand and vehicle mass are determined iteratively
- ICEV and HEV fuel economy based on industry comments and ADL analysis
  - Unnasch, S., "Fuel-Cycle Energy Impacts of Light-Duty Vehicles", Prepared for California Energy Commission, June 2000
  - ADL, "U.S. Light-duty Dieselization Scenarios - Preliminary Study Final Report", prepared for American Petroleum Institute, July 1999
- FCV fuel economy based on ADL analysis
  - FCV power unit performance curves based on ADL projections
    - kinetic and thermodynamic analyses using the full load assumptions from ADL/DOE analysis of automotive fuel cell systems
  - Motor and power electronic performance curves from Hauer, *Power Electronics*, SAE 2001-01-0543



Appendix Vehicle Analysis Assumptions *Fuel Economy Calculations*

The following assumptions were used in the vehicle model to determine overall performance and cost.

Vehicle Model Assumptions	

• 2010 Model Year - modest weight reductions
• Vehicle Use: 14,000 miles per year
• Acceleration
  • Time to 60mph from stop <11.5s
  • Time to 60 mph from 40mph <5.0s
• Top Speed 105 mph
• Hill Climbing
  • 55 mph
  • 6.5% grade
• Ambient Air Density 1.18 kg/m^3
• Gasoline Energy Density: 119,200 MJ/gallon
	Mid-sized Vehicle
	• Glider Weight 900 kg
	• Drag Coefficient 0.28
	• Vehicle Frontal Area 2.2 m^2
	• Rolling Resistance Coefficients
	  • Ad .008
	  • Bd 1.42E-5
	Sport Utility Vehicle
	• Glider Weight 1050 kg
	• Drag Coefficient 0.38
	• Vehicle Frontal Area 2.6 m^2
	• Rolling Resistance Coefficients
	  • Ad .010
	  • Bd 1.42E-5

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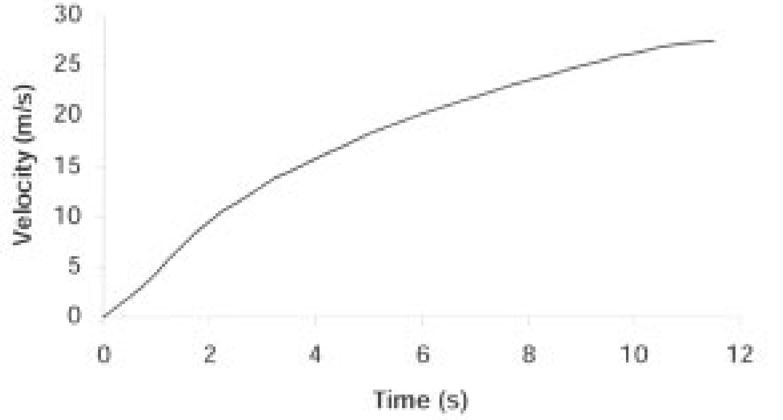
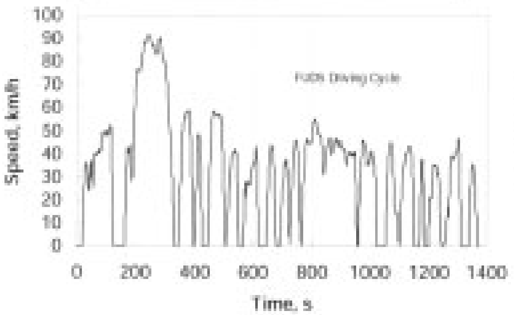
24

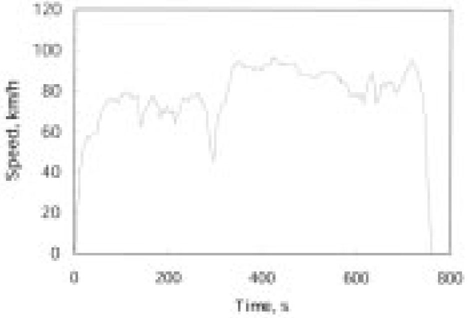
Powertrain sizing for all vehicles was based on meeting the same acceleration requirements.

Acceleration Profile



Fuel consumption was estimated for the EPA city and highway driving cycles.


City Driving Cycle (FUDS)


Highway Driving Cycle (HFET)

- Fuel consumption was calculated from the powertrain performance curves and drive cycle power requirements
- Our fuel economy results are based on CAFÉ fuel economy weightings:

Weighted fuel economy = 100/(55/City FE + 45/Highway FE)

Start-up energy demand represents a significant portion of the energy for FCVs with on-board reformers.

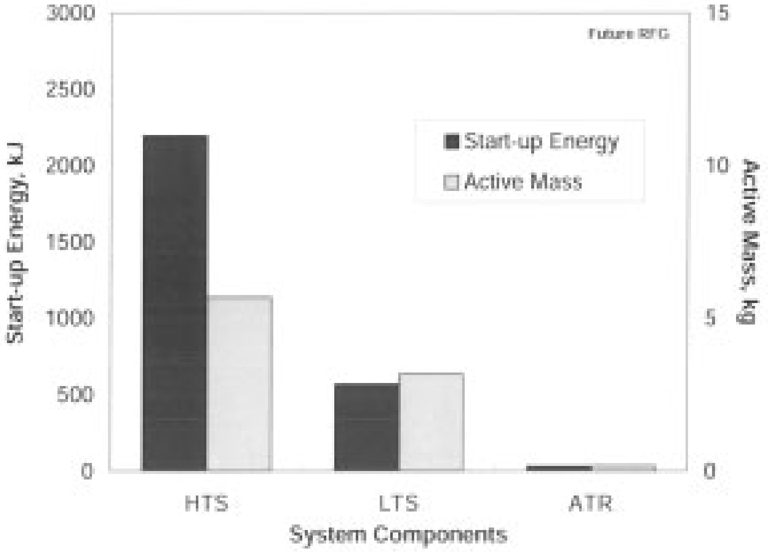
- ADL modeled energy inputs based on catalyst volume, heat capacity, system mass, and operating temperature
  - Start-up energy requirements are dictated by the energy input to the catalyst beds
  - Fuel cell generates power with hydrogen feed, even at low temperatures, so no start-up energy input is required
- Start-up energy inputs may need to occur twice a day for typical driving and represents up to 10 percent of the drive-cycle energy
  - Significant mass reductions in the fuel processor catalyst beds are projected

Energy requirements for future RFG ATR and Methanol SR FCVs

Fuel Processor, power unit size		Active Mass, kg	Start-up Energy, kJ	City Drive-cycle, kJ	Hywy Drive-cycle, kJ
RFG ATR	60 kW	9.0	2,800	17,700	21,900
	38 kW	5.7	1,770	15,600	20,600
Methanol SR	60 kW	8.8	2,260	17,700	21,900
	38 kW	5.6	1,430	15,600	20,600

The start-up energy requirement for system components decreases with active mass.

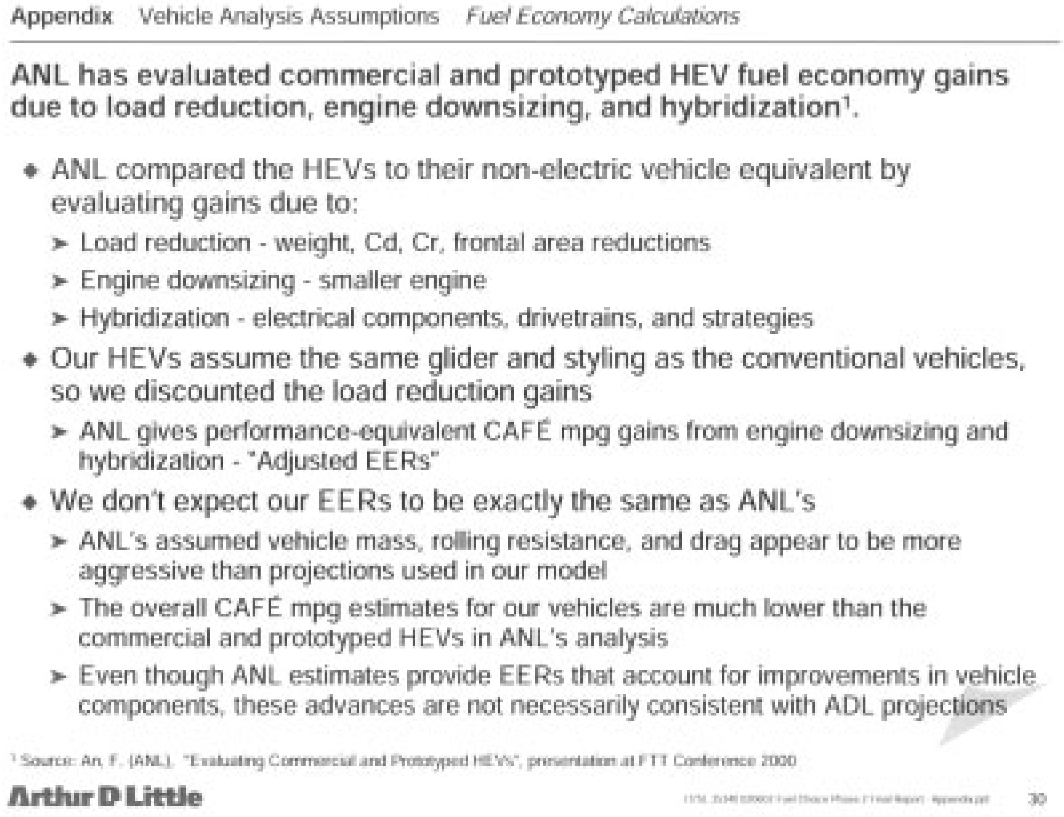
System component requirements for future 60 kW RFG FCVs



Starting the entire ATR represents a large fraction of the energy on a typical drive-cycle. Partial start-up of hybrids will reduce energy use.

- Partitioning the catalyst beds into 4 independent systems can improve turndown and cold start
  - Partial start-up on 25% of the HTS reduces start-up energy
  - Applicable to hybrid configurations where batteries can power the vehicle
- Waste heat from the ATR system and anode gas can be used to warm up the remainder of the HTS

Energy requirements for future RFG ATR FCVs					CAFE Fuel Economy mpg
Fuel Processor, start-up fraction		Start-up Energy, kJ	City Drive-cycle, kJ	Hywy Drive-cycle, kJ	
RFG ATR, 60 kW	100%	2,800	17,700	21,900	45.6
RFG ATR, 38 kW Large Battery Hybrid	100%	1,770	15,600	20,600	52.2
	25%	440	15,600	20,600	56.1
		Partitioned start-up saves fuel			



ANL has evaluated commercial and prototyped HEV fuel economy gains due to load reduction, engine downsizing, and hybridization[1].

- ANL compared the HEVs to their non-electric vehicle equivalent by evaluating gains due to:
  - Load reduction - weight, Cd, Cr, frontal area reductions
  - Engine downsizing - smaller engine
  - Hybridization - electrical components, drivetrains, and strategies
- Our HEVs assume the same glider and styling as the conventional vehicles, so we discounted the load reduction gains
  - ANL gives performance-equivalent CAFÉ mpg gains from engine downsizing and hybridization - "Adjusted EERs"
- We don't expect our EERs to be exactly the same as ANL's
  - ANL's assumed vehicle mass, rolling resistance, and drag appear to be more aggressive than projections used in our model
  - The overall CAFÉ mpg estimates for our vehicles are much lower than the commercial and prototyped HEVs in ANL's analysis
  - Even though ANL estimates provide EERs that account for improvements in vehicle components, these advances are not necessarily consistent with ADL projections

[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000

Our projections for gasoline HEV performance are in line with ANL's adjusted EERs.

ANL Analysis of Gasoline HEVs[1]					
HEV Name	**Type**	**Status**	**Battery Power[2]**	**CAFÉ mpg**	**Adjusted EER**
Japan Prius	Gasoline Mid-sized	Commercial	41.0%	54	1.51
U.S. Prius	Gasoline Mid-sized	Commercial	38.7%	58	1.62
Nissan Tino	Gasoline Mid-sized	Commercial	18.6%	48	1.30
Honda Insight	Gasoline Small	Commercial	16.7%	76	1.36
ADL Projections					
Large Battery HEV	Gasoline Mid-sized	Projected 2010	45%	44	1.45
Small Battery HEV	Gasoline Mid-sized	Projected 2010	9%	37	1.22

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[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Our projections for diesel HEVs are also in line with ANL's analysis, although all of these vehicles are prototypes.

ANL Analysis of Diesel HEVs[1]					
HEV Name	**Type**	**Status**	**Battery Power[2]**	**CAFE mpg**	**Adjusted EER**
GM Precept	Diesel Mid-sized	Concept Prototype	44.3%	80	1.64
DC ES X3	Diesel Mid-sized	Concept Prototype	31.2%	72	1.51
Ford Prodigy	Diesel Mid-sized	Concept Prototype	21.4%	70	1.46
ADL Projections					
Large Battery HEV	Diesel Mid-sized	Projected 2010	44%	47	1.54
Small Battery HEV	Diesel Mid-sized	Projected 2010	9%	44	1.42

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[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Most of this analysis focuses on fuel cell vehicles, but hydrogen burned in ICEs could be an important transition technology.

- Hydrogen internal combustion engines (ICEs) have efficiency comparable to diesel ICEs and emissions comparable to fuel cells
    - ➢ 30% higher efficiency than gasoline ICEs resulting from higher compression and specific heat ratios
    - ➢ Order of magnitude lower NO_x emissions compared to gasoline ICEs and no other significant emissions besides water vapor
- Lower power density than gasoline ICEs due to hydrogen's very low energy content per unit volume
- While a hydrogen ICE will be more efficient, it comes with a significant fuel weight and volume penalty
    - ➢ 320 liters of fuel (assuming 5,000 psia storage pressure) and 100 kg of fuel and tank weight compared to 45 liters and 35 kg for gasoline ICEV
        - Assuming 350 mile range, 40 and 30 mpgge for hydrogen and gasoline ICEVs, respectively
    - ➢ We did not accommodate additional volumetric capacity in vehicle design assumptions

We assumed an EER of 1.28 due to the added fuel tank and engine weight.

Data from existing electric drive vehicles was collected so we could compare to ADL projections of electric versus ICE power requirements.

Electric Drive Powertrain Data

MY	Manufacturer	Country (prod)	Vehicle	Engine/FC	Battery	Baseline[1]
2001	Daimler-Chrysler	Germany	Necar 5	75	0	75
2001	Ford	US	Focus	80	0	82
2001	GM/OPEL	Germany	HydroGen1	80	0	75
2001	Hyundai	US	Santa Fe	75	0	84
2000	Honda	Japan	FCX-V3	62	0	86
2000	Ford	US	P2000 Contour	67	0	127
1998	Toyota	US	RAV4 EV	0	57	95
1999	Ford	US	Ranger EV	0	84	112
1998	Chevrolet	US	S-10 EV	0	99	134
2001	EPRI-Report	model study[2]	EPRI S0	89	0	127
2001	EPRI-Report	model study[2]	EPRI HEV0	44	19	127
2001	EPRI-Report	model study[2]	EPRI HEV0 LW	40	17	98
2004	GM	US	Paradigm SUV	164	24	202
1998	Audi[3]	Germany	Duo	38	29	84
2001	Toyota	US	Prius	52	33	80

[1] Baseline vehicle selection criteria:

a) Choose a production vehicle with similar market segment or platform as the advanced vehicle manufacturer.

b) For baseline vehicles with several powertrain options, the comparison is based on:

2 options: lower power rating

3 or more options: second lowest power rating

[2] Modeling studies, all with zero all electric range. S0 - series, HEV0 - parallel, HEV0 LW - parallel with lightweight glider. HEV0 configurations have additional peak acceleration capability from the battery.

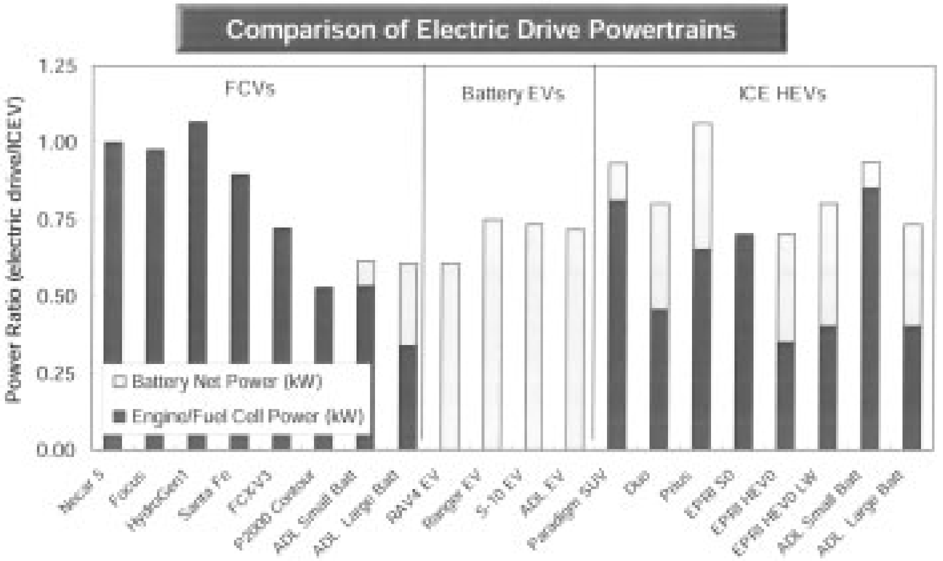
[3] The Audi Duo has 67 kw of ICE power and 29 of motor power, but it cannot use both simultaneously. This calculation rates the abttery power as a fraction of peak power (67kW) and not the "total" power (67+29=96kW)

Powertrain power levels are based on values published by developers.

Electric Drive Powertrain Data Sources

Manufacturer	Vehicle	Information Sources EV_HEV_FCV Comparison.xls
Daimler-Chrysler	Necar 5	www.mercedesbenz.com/e/innovation/fmobil/fuelcell/necar5.html
Daimler-Chrysler	Sprinter Van	www.mercedesbenz.com/e/innovation/fmobil/fuelcell/sprinter
Toyota	Prius	www.toyota.com/details/specs.html
Honda	Insight	www.honda2001.com/models/insight/specs/specs0.html
Nissan	Altra EV Wagon	www.nissandriven.com/insideNissan/LookingAheadArticle/0,9401,535,00.html
Ford	Focus FCV	Automotive Engineering International, June 2001, pgs. 25-28
GM	Paradigm SUV	www.gm.com/company/gmability/environment/gm_and_the_env/releases/paradigm_hev_010401.html
GM/Opel	HydroGen1	www.gm.com/company/gmability/environment/products/fuel_cells/gapc_h1.html
Model Study	EPRI HEV0	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Model Study	EPRI HEV0 LW	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Model Study	EPRI S0	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Hyundai	Santa Fe	Hyundai promotional handout
Audi	Duo	www.caranddriver.com/sp/Caranddriver/roadtests/1997/July/199707_roadtest_audi_duo.xml?keywords=Audi%20Duo
Toyota	RAV4 EV	ev.inel.gov/fop/eva/toyrav98.html
Ford	Ranger EV	ev.inel.gov/fop/eva/ford99.html
Chevrolet	S-10 EV	ev.inel.gov/fop/eva/s10.html
Ford	P2000 Contour	www.thinkmobility.com/technologies/fordp2000.pdf
Honda	FCX-V3	www.honda2001.com/news/press.html?=2001&r=509, popularmechanics.com

In most cases, the electric drive power requirements were lower than their ICE counterparts, consistent with our projections.



The comparisons are empirical and not always consistent.

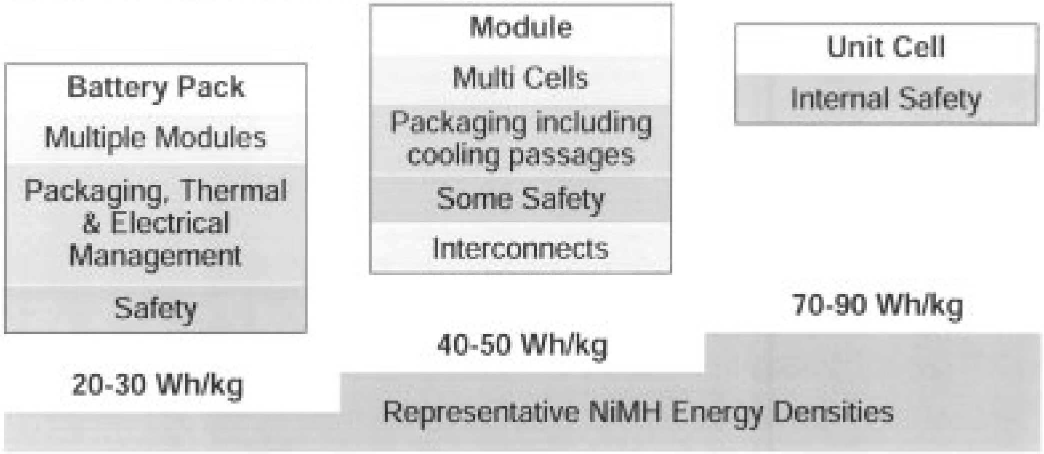
The range of power and energy specifications being pursued for HEVs reflects different vehicle requirements and design philosophies.

HEV Name	Status	Battery	Voltage	Energy (kWh)	Power (kW)	Battery Power[1]
Japan Prius	Commercial	NiMH	274	1.8	34	41.0%
Nissan Tino	Commercial	Li Ion	175	1.2	20	18.6%
Honda Insight	Commercial	NiMH	144	0.9	10	16.7%
GM Precept	Concept Prototype	NiMH or Li Polymer	350	3.0	25 peak 16 cont.	44.3%
DC ES X3	Concept Prototype	Li Ion	165		21	31.2%
Ford Prodigy	Concept Prototype	NiMH	288	1.1	35 peak 8 cont.	21.4%

* Values are estimated from literature data.

[1] Source: An, F. (ANL). "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000. Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

It is important to keep in mind the ancillary components, especially when quoting energy and power densities.



Battery Pack
Multiple Modules
Packaging, Thermal & Electrical Management
Safety

Module
Multi Cells
Packaging including cooling passages
Some Safety
Interconnects

Unit Cell
Internal Safety

Lithium battery technology offers the highest performance in the long-term, as has been shown in portable electronics.

Battery Technology	Pb Ac (VRLA)	NiMH	Li Ion
Application	42 V Startup	Power Assist/Regen. (PA/R)	PA/R, Full HEV
Cell Energy Density, Wh/kg	35	45-60	100-120
Battery Energy Density, Wh/kg	35	20-50	50-100
Battery Power Density, W/kg		500-1,000	600-1,500
Cost[1] - current (projected), $/kWh	200-300 (100-150)	1,000-1,500 (400-500)	>1,500 (TBD)
Strengths	• Low Cost	• Most Demonstrated • High Power	• Highest Energy and Power Density
Issues	• Cycle Life • Energy & Power Density • Primarily 42 V Application	• Life • High Temp Charging • Low Temp Performance • Cost	• Life • Low Temp Performance • Cost • Safety

[1] Does not include thermal and electrical management of battery.

We assumed the DOE compressor/expander module (CEM) efficiency goals would be met by 2010 and used them to calculate CEM parasitic power.

Percent of Flow	DOE Goals			System P Drop[1], bar
	Inlet P, bar	Compress Efficiency	Expander Efficiency	
100%	3.2	75%	90%	0.40
80%	3.2	80%	90%	0.26
60%	2.7	75%	86%	0.09
40%	2.1	70%	82%	0.01
20%	1.6	65%	80%	0.00
10%	1.3	50%	75%	0.00

* These goals have been established for a CEM likely to operate on a 50 kWe net fuel cell system. Larger CEMs could have better efficiency.

[1] Estimated based on ANL and ADL analysis assumptions. A detailed analysis has not been performed.

Although simultaneously achieving cost and weight goals will be challenging.

Parasitic loads are calculated from the required flowrates and temperatures determined by thermodynamic modeling and other assumptions.

Parasitic Assumptions at 50 kW Rated Power	Units	Gasoline ATR	Methanol SR	Hydrogen
Compressor flowrate[1]	kg/s	0.065[2]	0.048	0.048
Expander flowrate[1]	kg/s	0.066[3]	0.053[3]	0.048[4]
Expander inlet temp	°C	255[3,5]	150[3,6]	230[4]
Other parasitics[7]	kW	0.5	0.5	0.5
Motor efficiency	%	95	95	95

[*] Based on thermodynamic analysis of 50 kW fuel cell systems. A detailed system analysis with complete heat integration has not been performed. Conditions are consistent with the future scenario assumptions (i.e. high temperature membrane, 100% excess air, etc.).

[1] Flowrates are determined by iteration with the gross power requirement.

[2] Additional air required for the ATR.

[3] Assumes 85% anode fuel utilization with a tailgas burner and water is removed from the fuel cell exhaust as needed for the reformer.

[4] Assumes 95% anode fuel utilization with a tailgas burner.

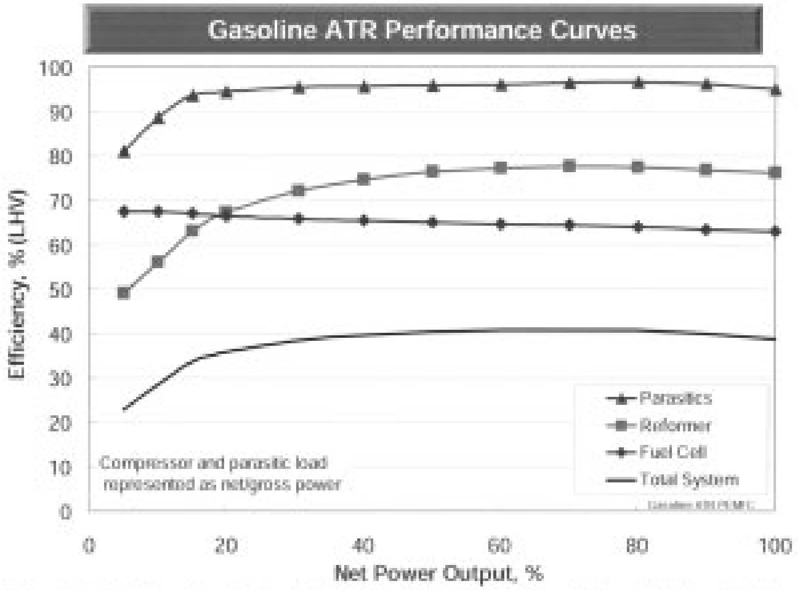
[5] The tailgas burner heat is used to vaporize the fuel prior to entering the expander.

[6] The tailgas burner heat is used to drive the steam reforming reaction prior to entering the expander.

[7] Includes pumps and fans.

Part load inputs are estimated based on these full load assumptions.

Voltage curves, parasitic loads, and reformer performance assumptions were used to generate performance curves for each system configuration.



* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis.

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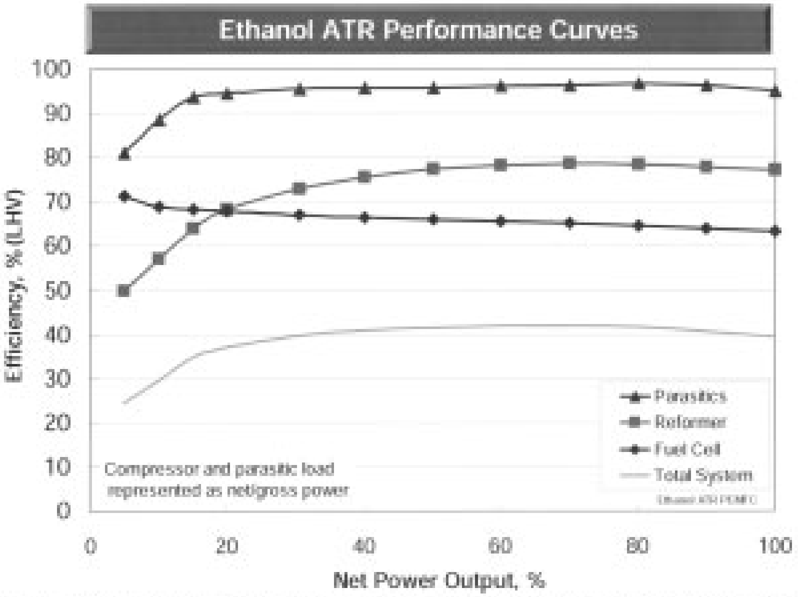
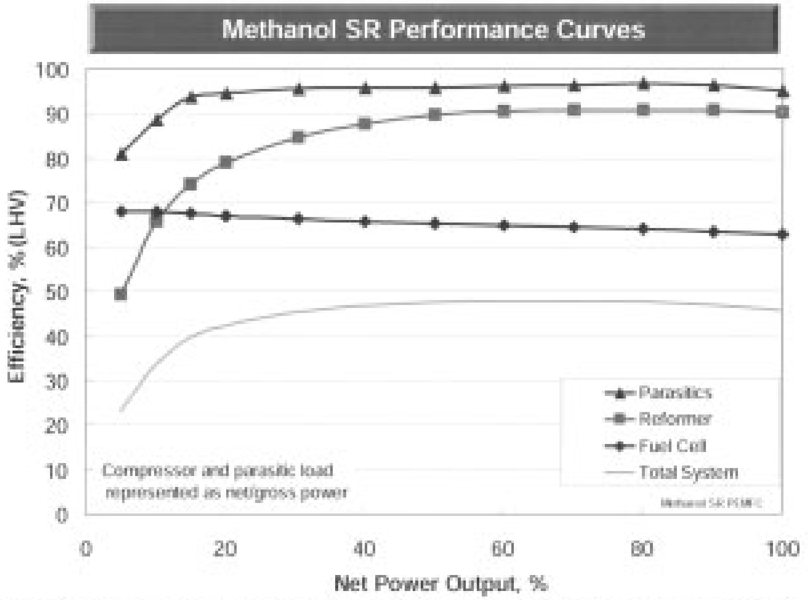
The assumed ethanol performance curve is very similar to the gasoline case.



* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis.

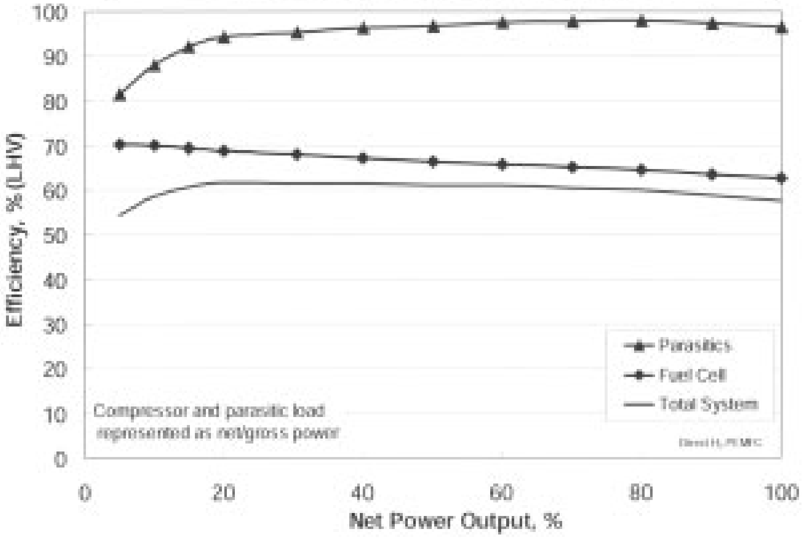
The overall methanol efficiency is better than the gasoline and ethanol cases due to the higher efficiency of the steam reformer.


Methanol SR Performance Curves

* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis. Note: Actual reformer efficiency remains near 91%. Anode utilization would be decreased to provide additional fuel for the reformer.

Lacking a reformer, the direct hydrogen system is much more efficient, especially at part load.

Direct Hydrogen Performance Curves



Compressor and parasitic load represented as net/gross power

* Total system efficiency includes 95% anode utilization efficiency.

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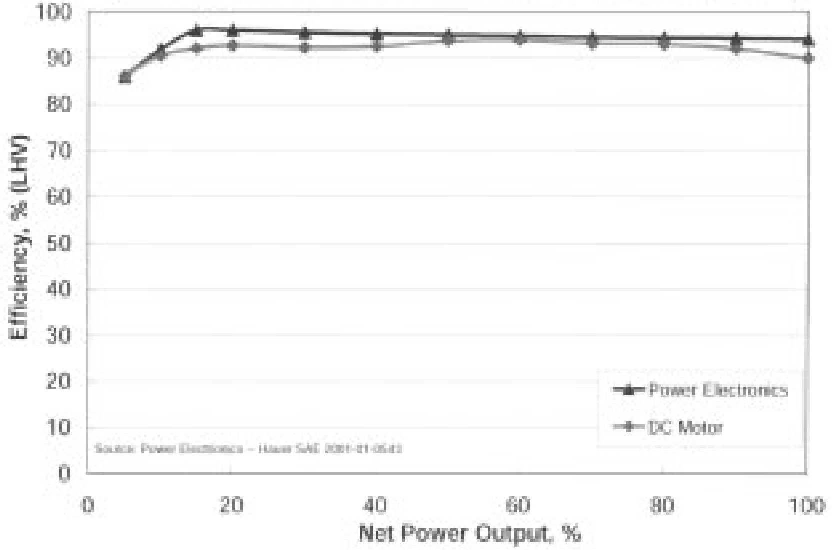
In addition to the power unit, motor and power electronic performance curves were applied to the overall powertrain performance.

Motor and Power Electronic Performance Curves



Source: Power Electronics – Hauer SAE 2001-01-0543

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Key assumptions for vehicle ownership cost:

- Vehicle cost assumptions:
  - Monthly payments over 5 years
  - Adjusted for resale value: assumed to be 39% for the vehicle minus the precious metals which are assumed to have 85% residual value
  - 4% finance rate
  - Insurance, tax and license costs are excluded[1]
  - Glider cost is assumed to be the same for all vehicles in the same class[2]
- Maintenance cost assumptions:
  - Maintenance costs based on ADL/EPRI HEV study (EPRI 2001)
  - Assume identical maintenance costs for all vehicles in the same class
    - Customer expectation is that maintenance will be at least as good as conventional vehicles
    - No real world data
    - Limited data from battery EVs suggests same cost, although warranty costs for first commercial vehicles are high for some EV manufacturers
- Fuel cost assumptions:
  - Fuel costs are based on 14,000 mi/yr driving, fuel economy analysis, and fuel cost analysis
  - Tax excluded[3]

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[1] Would be higher for more costly vehicles under current practices.

[2] In practice, some changes to the glider would be required to accommodate differences in vehicle mass, brakes, and fuel storage.

[3] Would be lower for more fuel efficient gasoline and diesel vehicles. Road tax on hydrogen and electricity would be zero.

Consistent assumptions were used for the common powertrain weights for ICEVs, HEVs, FCVs, and Battery EVs.

Powertrain Parameters

Component	Value	Unit
Mass estimates, light-weight vehicles		
Mid-size glider mass	900	kg
SUV glider mass	1050	kg
Engine, Misc.		
Engine Misc, V6, ICEV	38.7	kg
Engine Misc, parallel HEV	10	kg
Engine Mounts	5	kg
FC mounts	5	kg
Electrical, Misc.		
Battery Pack, Tray Hardware 9kW	15	kg
Battery Pack, Tray Hardware 50kW	25.5	kg
Motor/electronics Thermal	16.6	kg
Battery Thermal	14.6	kg
Power Transmission		
HEV Transmission	50	kg
V6 Transmission/ICE Weight	1.30	kW/kg
Power Controls (HEV inverter)	5	kg
Power Controls (EV inverter)	7	kg
Midsized Fixed Battery Power	9	kW
Midsized Fixed Fuel Cell Power	Varies with vehicle weight	

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*. Palo Alto, June 2001.

Internal Combustion Engine costs depend upon fuel type and power rating. Smaller engines could be used in full parallel HEVs.

IC Engine Parameters

Engine Type	Intercept ($ @ 0 power)	Cost ($/kW)	Power Density (kW/kg)
RFG L4 ICE	$424	12	0.73
Diesel I4 ICE	$636	18	0.73
RFG V6 ICE	$693	10.9	0.78
Diesel V6 ICE	$1,040	16.4	0.78
Hydrogen ICE Cost Premium	$400	--	0.59

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, June 2001.

Arthur D. Little, *U.S. Light-duty Dieselization Scenarios - Preliminary Study Final Report*, prepared for American Petroleum Institute, July 1999.

We used ADL cost model projections for fuel cell and fuel processor costs.

Fuel Cell and Fuel Processor Parameters

Vehicle Component	ADL Projection	Unit	ADL Projection	Unit
Fuel Cell Type				
ATR FC (62 kW)	62.3	$/kW	0.596	kW/kg
MeOH FC (62 kW)	56.1	$/kW	0.676	kW/kg
EtOH ATR FC (62 kW)	62.3	$/kW	0.596	kW/kg
cH2 FC (59 kW)	50.5	$/kW	0.786	kW/kg
MH FC (59 kW)	50.5	$/kW	0.786	kW/kg
ATR FC (39 kW)	72.9	$/kW	0.544	kW/kg
MeOH FC (39 kW)	66.6	$/kW	0.613	kW/kg
cH2 FC (39 kW)	59.5	$/kW	0.720	kW/kg

Vehicle Component	ADL Projection	Unit
Precious Metals		
V6 Catalyst Precious Metals	250	$/unit
L4 Catalyst Precious Metals	180	$/unit
Assume same cost for diesel cat		
RFG FC and ATR	16.9	$/kW
Direct H_2 Fuel Cell	14.4	$/kW
MeOH FC and SR	10.3	$/kW

Vehicle Component	ADL Projection	Unit	ADL Projection	Unit
Fuel Processor				
ATR FP (62 kW)	23.4	$/kW	1.41	kW/kg
MeOH SR FP (62 kW)	21.4	$/kW	1.43	kW/kg
ATR FP (39 kW)	32.6	$/kW	1.13	kW/kg
MeOH SR FP (39 kW)	30.5	$/kW	1.13	kW/kg

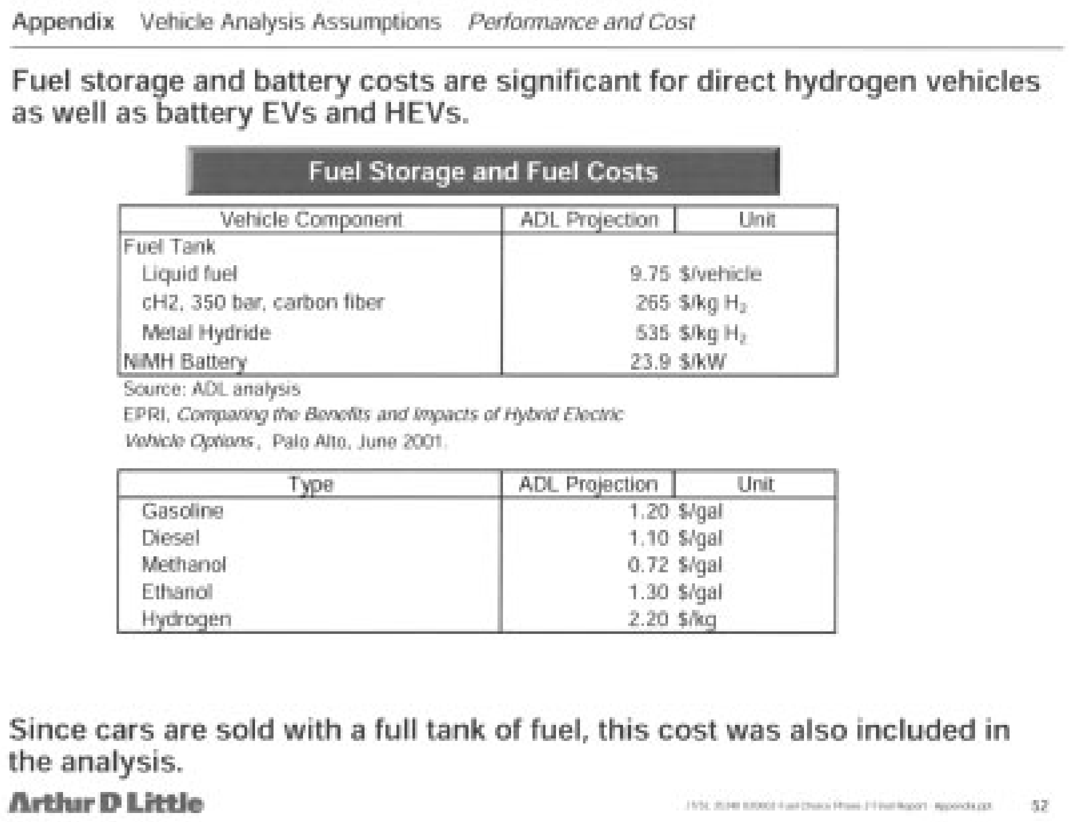
Source: ADL analysis, fuel cell cost model

Consistent assumptions were used for the common HEV, FCV, and Battery EV powertrain costs.

Powertrain Parameters

Vehicle Component	Value	Unit
Radiator		
ICE (127 kW)	0.236	$/kW
Fuel Cell System (62 kW)	4.48	$/kW
Transmission		
ICE (127 kW)	1045	$/vehicle
HEV, parallel	625	$/vehicle
Motor intercept	190	$/unit
Motor slope	13.7	$/kW
Power Controls intercept	411	$/unit
Power Controls slope	18.9	$/kW
Exhaust/Evaporative	250	$/vehicle
Accessories	250	$/vehicle

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Palo Alto, June 2001.



Fuel storage and battery costs are significant for direct hydrogen vehicles as well as battery EVs and HEVs.

Fuel Storage and Fuel Costs

Vehicle Component	ADL Projection	Unit
Fuel Tank		
Liquid fuel	9.75	\$/vehicle
cH2, 350 bar, carbon fiber	265	\$/kg H_2
Metal Hydride	535	\$/kg H_2
NiMH Battery	23.9	\$/kW

Source: ADL analysis

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Palo Alto, June 2001.

Type	ADL Projection	Unit
Gasoline	1.20	\$/gal
Diesel	1.10	\$/gal
Methanol	0.72	\$/gal
Ethanol	1.30	\$/gal
Hydrogen	2.20	\$/kg

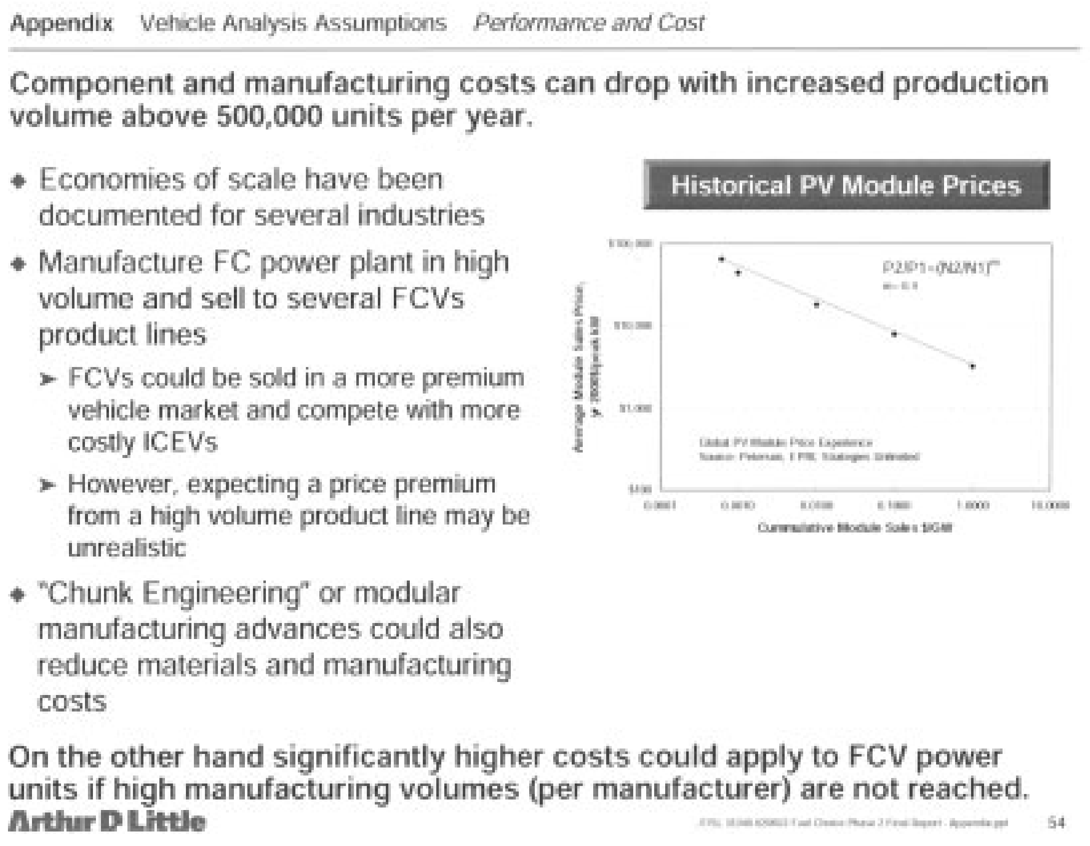
Since cars are sold with a full tank of fuel, this cost was also included in the analysis.

Vehicle costs are marked up to a retail price equivalent for the ownership cost analysis.

Price and Cost Parameters

Item	Value	Unit
Glider	7255	$/vehicle
Manufacturer Markup	1.50	$/$cost
Dealer Markup (Post-manuf)	1.163	$/(cost+mrk up)
Combined Markup	1.745	$/$cost
Max. Markup for Engine/Fuel Cell	2500	$/vehicle
Max. Markup for Traction Battery	1000	$/vehicle

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Palo Alto, June 2001.



Component and manufacturing costs can drop with increased production volume above 500,000 units per year.

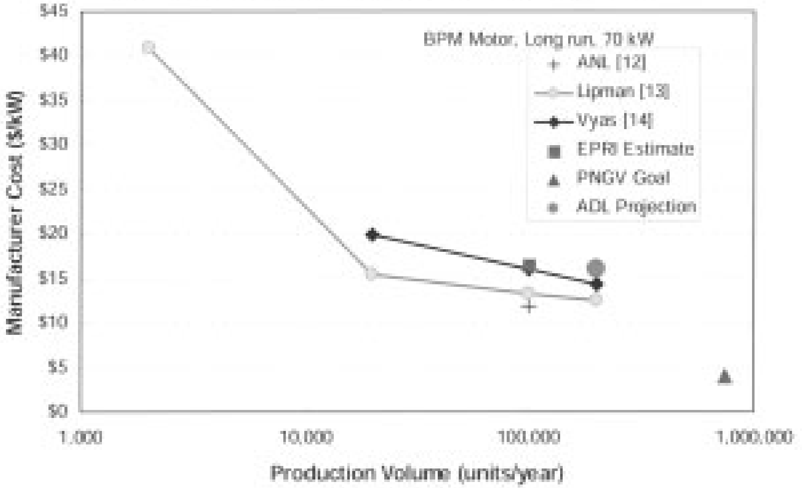
- Economies of scale have been documented for several industries
- Manufacture FC power plant in high volume and sell to several FCVs product lines
  - ➢ FCVs could be sold in a more premium vehicle market and compete with more costly ICEVs
  - ➢ However, expecting a price premium from a high volume product line may be unrealistic
- "Chunk Engineering" or modular manufacturing advances could also reduce materials and manufacturing costs

Historical PV Module Prices

On the other hand significantly higher costs could apply to FCV power units if high manufacturing volumes (per manufacturer) are not reached.

ADL projections for EV components are within range of other studies but are more conservative than the PNGV goals.

Estimates for Electric Motor Costs



Using DOE's aggressive goals for EV components would reduce FCV costs in comparison to ICEVs and even HEVs.

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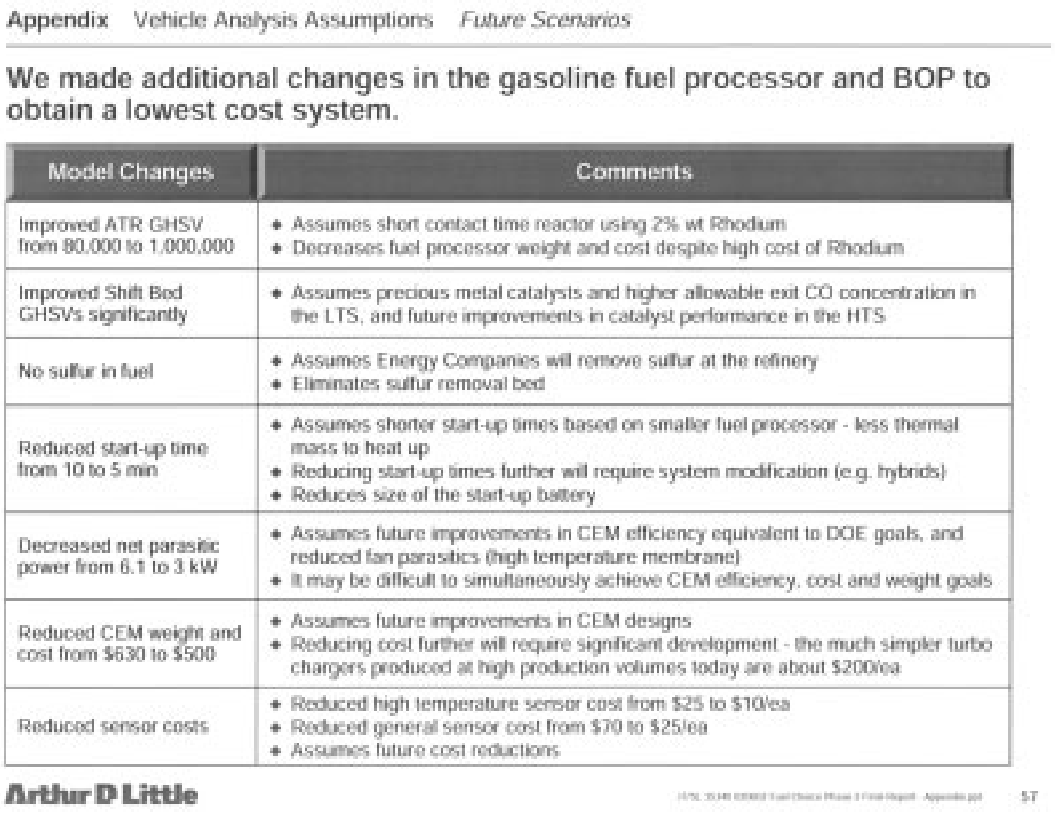
FCV power unit costs and performance built on ADL/DOE's current fuel cell system assumptions with the following changes to the stack.

Model Changes	Comments
Increased Membrane Operating Temperature from 80°C to 160°C	◆ Increases CO tolerance - eliminates PrOX and related equipment ◆ Assume reduced humidity requirements - eliminates cathode humidifying equipment eliminates low temperature water economizer and reformate cooler ◆ Assume reduced stack cooling requirements - fewer coolant plates per cell ◆ Increases radiator LMTD - reduces radiator size
Increased Current Density[1] from 310 to 500 mA/cm^2 at 0.8 V on gasoline reformate	◆ Based on expected improvements in CO tolerance, catalyst utilization and catalytic activity
Decreased Pt loading from 0.4/0.4 mg/cm^2 to 0.2/0.1 mg/cm^2 (Cathode/Anode sides)	◆ Based on modeling of polarization curve as a function of catalyst loading and ohmic resistances
Decreased Electrolyte Cost from 100 to 50 \$/m^2	◆ Basic materials are not intrinsically expensive ◆ Assumes high temperature membranes will not be significantly different in cost and will have equivalent performance
Decreased Platinum Processing Mark-up from 20% to 10%	◆ Assumes cost reductions at high volumes with future development

[1] Current density at 0.8 V, 0.2/0.1 mg/cm^2 (Cathode/Anode sides) Pt loading for the future case, 85% fuel utilization, 100% excess air, 3 atm operating pressure, and reformate with 1,000 ppm CO.



Appendix Vehicle Analysis Assumptions *Future Scenarios*

We made additional changes in the gasoline fuel processor and BOP to obtain a lowest cost system.

Model Changes	Comments
Improved ATR GHSV from 80,000 to 1,000,000	• Assumes short contact time reactor using 2% wt Rhodium • Decreases fuel processor weight and cost despite high cost of Rhodium
Improved Shift Bed GHSVs significantly	• Assumes precious metal catalysts and higher allowable exit CO concentration in the LTS, and future improvements in catalyst performance in the HTS
No sulfur in fuel	• Assumes Energy Companies will remove sulfur at the refinery • Eliminates sulfur removal bed
Reduced start-up time from 10 to 5 min	• Assumes shorter start-up times based on smaller fuel processor - less thermal mass to heat up • Reducing start-up times further will require system modification (e.g. hybrids) • Reduces size of the start-up battery
Decreased net parasitic power from 6.1 to 3 kW	• Assumes future improvements in CEM efficiency equivalent to DOE goals, and reduced fan parasitics (high temperature membrane) • It may be difficult to simultaneously achieve CEM efficiency, cost and weight goals
Reduced CEM weight and cost from $630 to $500	• Assumes future improvements in CEM designs • Reducing cost further will require significant development - the much simpler turbo chargers produced at high production volumes today are about $200/ea
Reduced sensor costs	• Reduced high temperature sensor cost from $25 to $10/ea • Reduced general sensor cost from $70 to $25/ea • Assumes future cost reductions

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We made additional assumptions that primarily affected overall system weight.

Model Changes	Comments
Decreased Bipolar Plate Material Density from 2.25 to 1.12 g/cm³	◆ Based on lighter weight material densities (such as GRAFOIL)
Decreased Width of Border around Fuel Cell Active Area from 1.5 to 1 inches[1]	◆ Increases cell active area significantly for high power density design points - reduces overall fuel cell stack size
Decreased Weight of Low Temperature Packaging Materials	◆ Assumes high density plastic materials instead of stainless steel for vessels less than 100°C
Included RAM Air in Radiator Analysis	◆ Based heat exchange coefficient on GM analysis of an automotive radiator for a fuel cell systems that takes RAM air effects into account ◆ Reduces radiator size significantly

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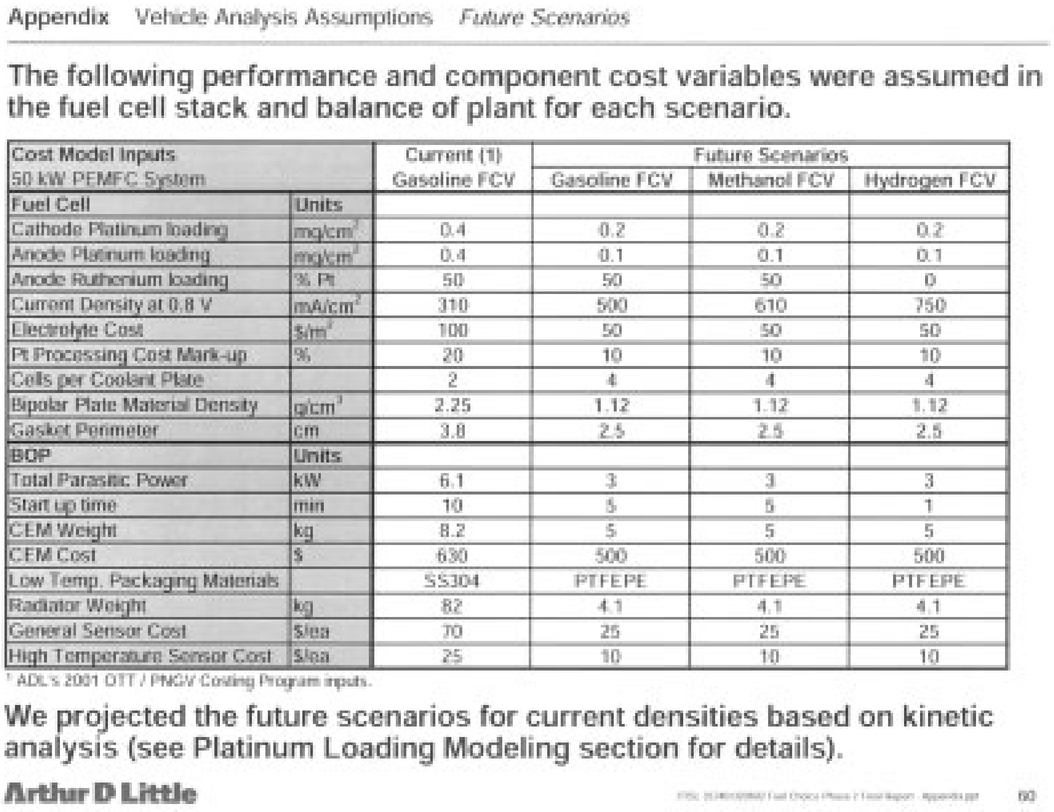
[1] Border required for gasket and flow passages.

For the direct hydrogen FCV scenario, we increase the power density and replaced the fuel processor with compressed hydrogen storage.

Model Changes	Comments
Increased Current Density[1] to 750 mA/cm^2 at 0.8 V	- Based on experimental data that shows 1.5 times improvement for hydrogen versus gasoline reformate fuel cells, and kinetic verification (see Platinum Loading Modeling section for details)
Eliminated Ruthenium (Ru) from the MEA	- Assumed there is no CO or CO_2 in the hydrogen
Decreased Start-up Time from 5 to 1 min	- No warm-up time associated with the fuel processor
Added Compressed Hydrogen Storage System at $1200 and 45 kg[2]	- Assuming carbon fiber-wrapped tank rated for 5,000 psi working pressure - Based on discussions with component developers - assuming high production volumes, future technology, including the whole storage system (tank, fuel injector, controls, safety) - A detailed analysis has not been performed to date
Eliminated Fuel Processor Components	- Fuel supply, reformate generator, reformate conditioner, fuel processor water supply
Eliminated Fuel Processor Start-up Components in the Tailgas Burner	- Fuel vaporizer, warm-up steam generator

[1] Current density at 0.8 V, 0.2/0.1 mg/cm^2 (Cathode/Anode sides) Pt loading for the future case, 95% anode utilization, 100% excess air, 3 atm operating pressure, and 100% hydrogen.

[2] Assumes 350 mile range, 80 mpgge fuel economy, and 10% storage wt percent based on current claims by developers.



The following performance and component cost variables were assumed in the fuel cell stack and balance of plant for each scenario.

Cost Model Inputs 50 kW PEMFC System		Current (1)	Future Scenarios		
		Gasoline FCV	Gasoline FCV	Methanol FCV	Hydrogen FCV
Fuel Cell	**Units**				
Cathode Platinum loading	mg/cm^2	0.4	0.2	0.2	0.2
Anode Platinum loading	mg/cm^2	0.4	0.1	0.1	0.1
Anode Ruthenium loading	% Pt	50	50	50	0
Current Density at 0.8 V	mA/cm^2	310	500	610	750
Electrolyte Cost	\$/m^2	100	50	50	50
Pt Processing Cost Mark-up	%	20	10	10	10
Cells per Coolant Plate		2	4	4	4
Bipolar Plate Material Density	g/cm^3	2.25	1.12	1.12	1.12
Gasket Perimeter	cm	3.8	2.5	2.5	2.5
BOP	**Units**				
Total Parasitic Power	kW	6.1	3	3	3
Start up time	min	10	5	5	1
CEM Weight	kg	8.2	5	5	5
CEM Cost	$	630	500	500	500
Low Temp. Packaging Materials		SS304	PTFEPE	PTFEPE	PTFEPE
Radiator Weight	kg	82	4.1	4.1	4.1
General Sensor Cost	$/ea	70	25	25	25
High Temperature Sensor Cost	$/ea	25	10	10	10

[1] ADL's 2001 OTT / PNGV Costing Program inputs.

We projected the future scenarios for current densities based on kinetic analysis (see Platinum Loading Modeling section for details).

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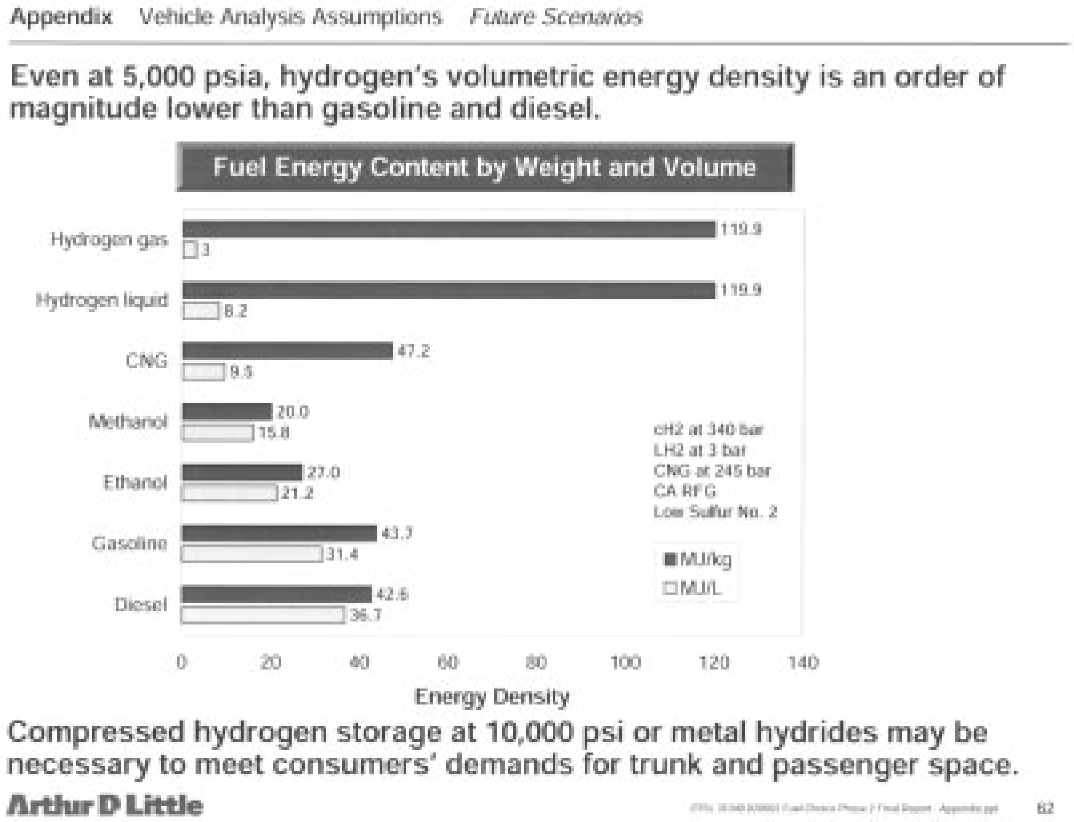
Fuel processor performance and component costs were also varied for each scenario.

Cost Model Inputs 50 kW PEMFC System		Current (1) Gasoline FCV	Future Scenarios Gasoline FCV	 Methanol FCV	 Hydrogen FCV
Fuel Processor	**Units**				
NH3 Bed		yes	yes	removed	NA
Space Velocities					
ATR1 (Precious metal)	hr^{-1}	80,000	1 MM	removed	NA
ATR2 (Ni)	hr^{-1}	15,000	removed	removed	NA
ZnO bed	hr^{-1}	45,000	removed	removed	NA
HTS	hr^{-1}	10,000	40,000	40,000	NA
LTS	hr^{-1}	5,000	80,000	80,000	NA
PrOX	hr^{-1}	10,000	removed	removed	NA
ATR1 Catalyst Cost	$/kg	81 (2)	630 (3)	removed	NA
ATR2 Catalyst Cost	$/kg	15 (4)	removed	removed	NA
LTS Catalyst Cost	$/kg	14 (5)	82 (2)	82 (2)	NA
cH_2 Storage	**Units**				
Hydrogen Storage Cost	$	NA	NA	NA	1200
Hydrogen Storage Weight	kg	NA	NA	NA	45

[1] ADL's 2001 OTT / PNGV Costing Program inputs.
[2] Less than 0.5% Platinum ($15/g).
[3] 2% Rhodium ($30/g).
[4] Ni+K based catalyst.
[5] Cu+Zn+Al based catalyst.

We assumed the methanol steam reformer costs would be similar to the water gas shift beds of the autothermal reformer.



Even at 5,000 psia, hydrogen's volumetric energy density is an order of magnitude lower than gasoline and diesel.

Fuel Energy Content by Weight and Volume

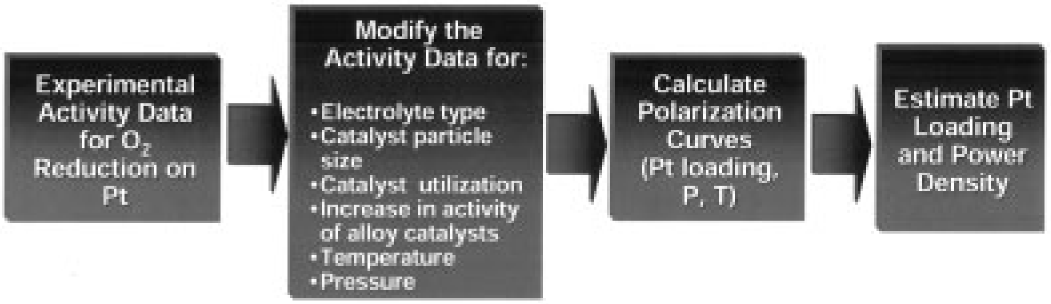
Compressed hydrogen storage at 10,000 psi or metal hydrides may be necessary to meet consumers' demands for trunk and passenger space.

Outline

Appendix

- Glossary
- Fuel Chain Analysis Assumptions
- Vehicle Analysis Assumptions
- **Platinum Loading Modeling**
- Additional Analysis Results
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- Target Setting
- Bibliography

Optimistic but physically attainable power densities for each fuel cell system were calculated based on kinetic analysis.



Experimental Activity Data for O_2 Reduction on Pt

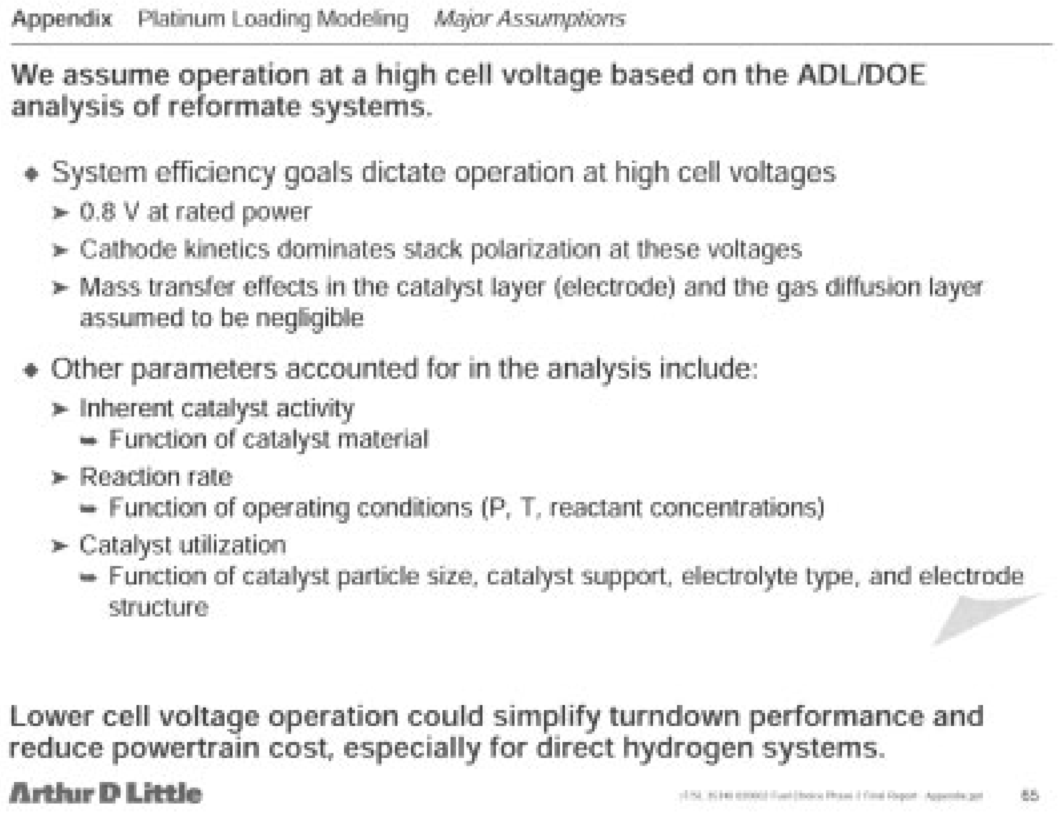
Modify the Activity Data for:

- Electrolyte type
- Catalyst particle size
- Catalyst utilization
- Increase in activity of alloy catalysts
- Temperature
- Pressure

Calculate Polarization Curves (Pt loading, P, T)

Estimate Pt Loading and Power Density

For the projection of future scenarios, we assume the availability of high temperature electrolyte technology with performance similar to current electrolytes.



We assume operation at a high cell voltage based on the ADL/DOE analysis of reformate systems.

- System efficiency goals dictate operation at high cell voltages
  - 0.8 V at rated power
  - Cathode kinetics dominates stack polarization at these voltages
  - Mass transfer effects in the catalyst layer (electrode) and the gas diffusion layer assumed to be negligible
- Other parameters accounted for in the analysis include:
  - Inherent catalyst activity
    - Function of catalyst material
  - Reaction rate
    - Function of operating conditions (P, T, reactant concentrations)
  - Catalyst utilization
    - Function of catalyst particle size, catalyst support, electrolyte type, and electrode structure

Lower cell voltage operation could simplify turndown performance and reduce powertrain cost, especially for direct hydrogen systems.

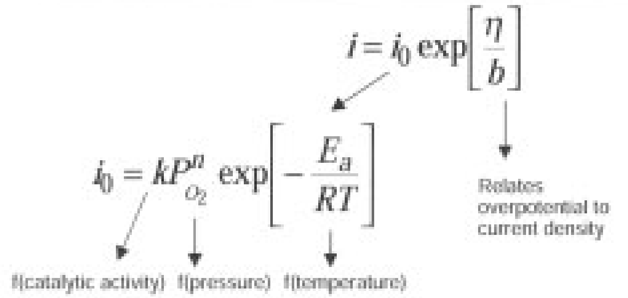
Catalysis loading, power density, and ohmic resistance are critical parameters that influence the active and inactive materials stack costs.

- Active Materials
  - Electrode material cost dominated by the catalyst material(s)
  - Catalyst loading determines the kinetics of the MEA
    - Anode catalyst loading assumed to equal 50% of the cathode loading
    - Assume 15% utilization (3.5 nm particle [30%], 50% available area)
    - Assume alloy catalyst with twice the activity of Pt
  - Electrode area for specified power and operating voltage determined by polarization curve
- Inactive Materials
  - Electrode area determines inactive material cost
  - Ohmic resistance of inactive materials influences polarization curve

Tafel kinetics is used to model the cathode current density versus overpotential for different catalyst activity and loading, pressure, and temperature.

- Assumptions:
  - Activity is defined as Amperes per unit Platinum surface area
  - Tafel kinetics
  - The Tafel slope is assumed constant for the temperature range considered

Tafel Kinetics



$$i = i_0 \exp\left[\frac{\eta}{b}\right]$$

$$i_0 = kP_{O_2}^{n} \exp\left[-\frac{E_a}{RT}\right]$$

η -Cathode Overpotential
b - Tafel Slope
E_a - Activation energy
k - pre-exponential factor
P_{O_2} - O_2 partial pressure
n - Reaction order
T - Temperature

For the future scenarios, we chose a cathode catalyst loading of 0.2 mg/cm² because of stack power density targets.

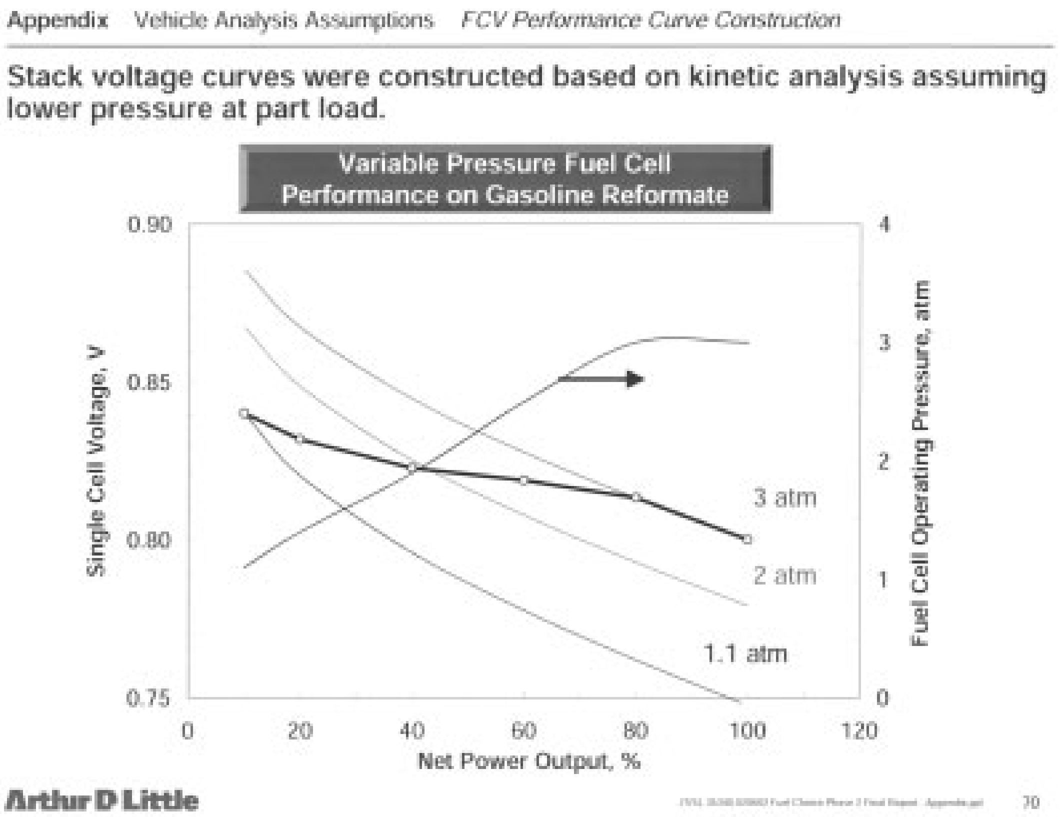
Assumptions	Hydrogen	MeOH Reformate	Gasoline Reformate
Cathode Pt Loading (mg/cm²)	0.2	0.2	0.2
Anode Pt Loading (mg/cm²)	0.1	0.1	0.1
Anode overpotential (mV)	0	18	30
Membrane Resistance (mΩ cm²)	50	50	50
Electronic Resistance (mΩ cm²)	20	20	20

Current Density (mA/cm²)	750	610	500

Operating Conditions:
0.8 V, 3 atm, 160 C, 3.5 nm Particles, 2x Pt activity

The specific currents estimated in this analysis correspond to a 'best case scenario' for platinum; lower currents would result at 0.8 V if:

- The catalyst area utilization is less than 50%
- Either ionic or molecular diffusion resistances in the catalyst layer become significant
  - Literature data indicates that current densities on the order of 2 A cm^{-2} are not diffusion limited for cells with supersaturated feed streams
  - However, the ionic resistance in the catalyst layer can become limiting for saturated or partially saturated feed streams
- The electrolyte resistance is greater than 0.05 Ω cm^{-2}
- If the solubility of oxygen in the high temperature electrolyte is lower than the solubility of oxygen in Nafion at room temperature
- Anode overpotentials are significantly greater than those assumed



Stack voltage curves were constructed based on kinetic analysis assuming lower pressure at part load.

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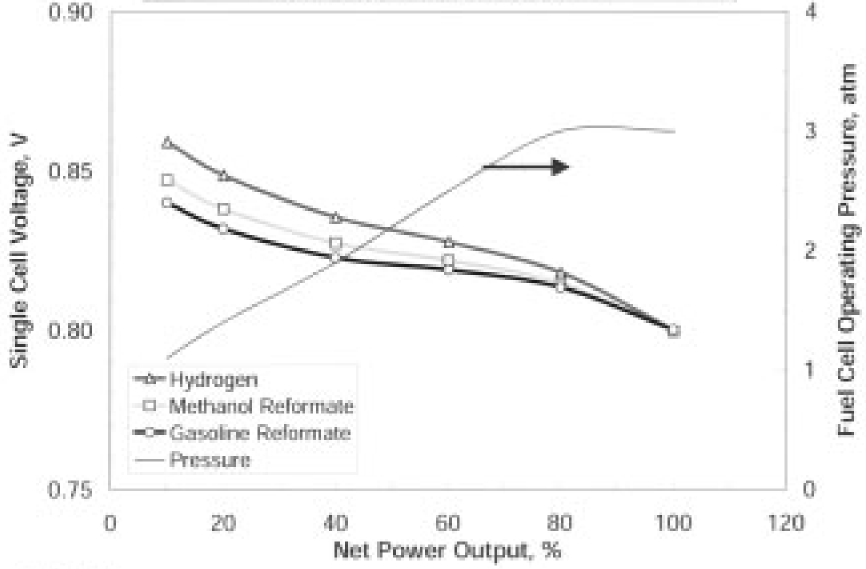
The direct hydrogen case allows for higher cell voltage operation (better efficiency) at part load.

Variable Pressure Fuel Cell Performance on Reformate and Hydrogen



Outline

Appendix

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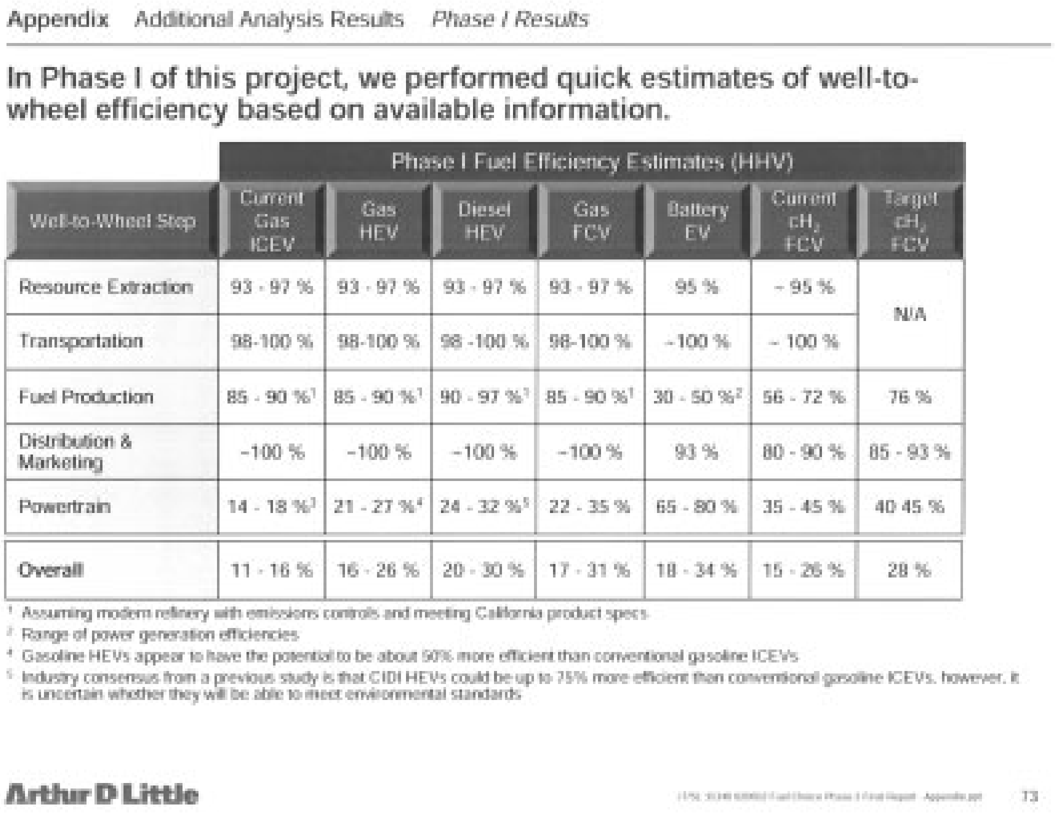
- **Additional Analysis Results**
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- Target Setting
- Bibliography



In Phase I of this project, we performed quick estimates of well-to-wheel efficiency based on available information.

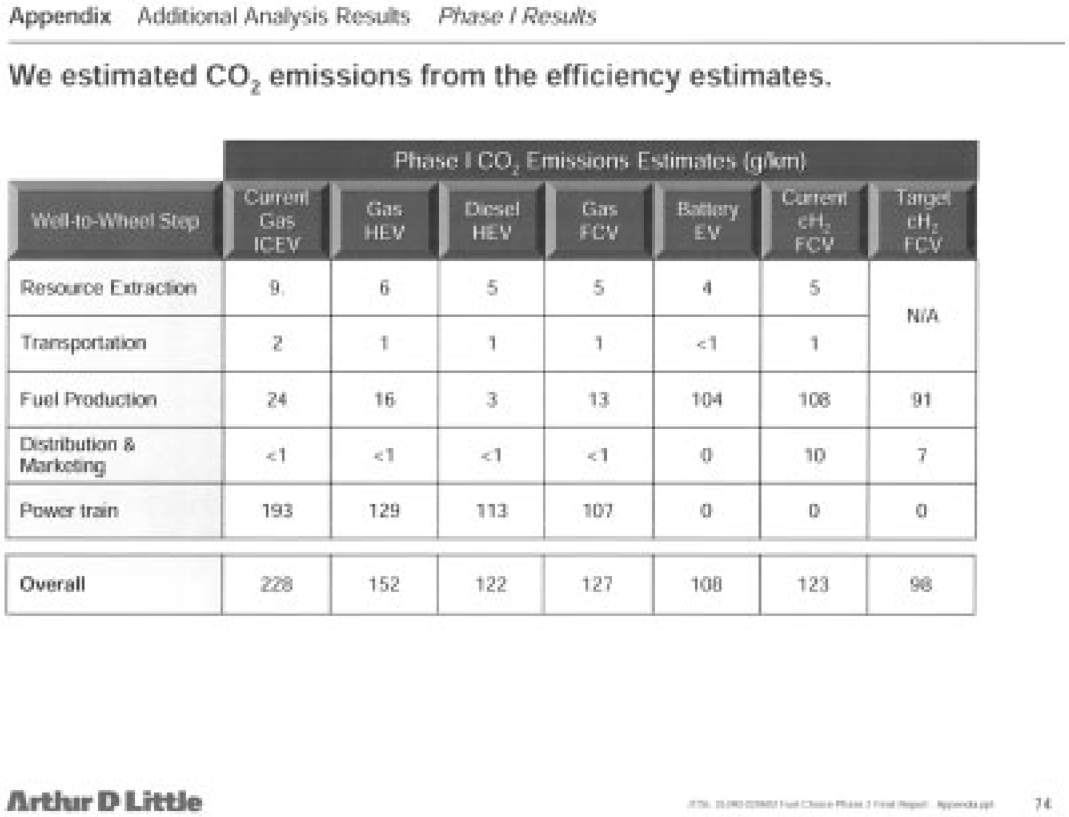
	Phase I Fuel Efficiency Estimates (HHV)						
Well-to-Wheel Step	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH_2 FCV	Target cH_2 FCV
Resource Extraction	93 - 97 %	93 - 97 %	93 - 97 %	93 - 97 %	95 %	~ 95 %	N/A
Transportation	98-100 %	98-100 %	98 -100 %	98-100 %	~100 %	~ 100 %	
Fuel Production	85 - 90 %[1]	85 - 90 %[1]	90 - 97 %[1]	85 - 90 %[1]	30 - 50 %[2]	56 - 72 %	76 %
Distribution & Marketing	~100 %	~100 %	~100 %	~100 %	93 %	80 - 90 %	85 - 93 %
Powertrain	14 - 18 %[3]	21 - 27 %[4]	24 - 32 %[5]	22 - 35 %	65 - 80 %	35 - 45 %	40 45 %
Overall	11 - 16 %	16 - 26 %	20 - 30 %	17 - 31 %	18 - 34 %	15 - 26 %	28 %

[1] Assuming modern refinery with emissions controls and meeting California product specs

[2] Range of power generation efficiencies

[4] Gasoline HEVs appear to have the potential to be about 50% more efficient than conventional gasoline ICEVs

[5] Industry consensus from a previous study is that CIDI HEVs could be up to 75% more efficient than conventional gasoline ICEVs, however, it is uncertain whether they will be able to meet environmental standards



Appendix Additional Analysis Results *Phase I Results*

We estimated CO_2 emissions from the efficiency estimates.

	Phase I CO_2 Emissions Estimates (g/km)						
Well-to-Wheel Step	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH_2 FCV	Target cH_2 FCV
Resource Extraction	9.	6	5	5	4	5	N/A
Transportation	2	1	1	1	<1	1	
Fuel Production	24	16	3	13	104	108	91
Distribution & Marketing	<1	<1	<1	<1	0	10	7
Power train	193	129	113	107	0	0	0
Overall	228	152	122	127	108	123	98

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Quick estimates of overall ownership cost were also developed in Phase I.

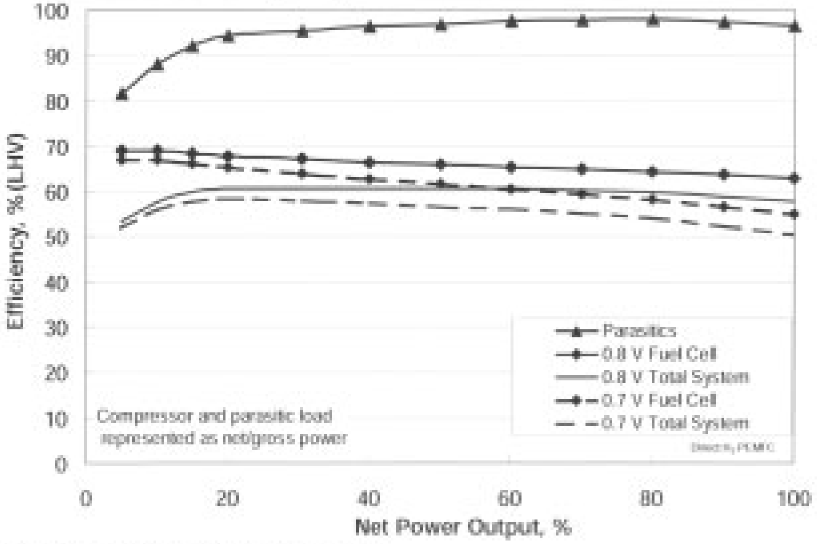
	Phase I Cost Estimates						
Ownership Cost Category	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH_2 FCV	Target cH_2 FCV
Fuel Cost ($/GJ)	7.86[1]	7.86[1]	7.86[1]	7.86[1]	13.89[2]	13.37	11
Fuel cost (ct/km)	2.2	1.5	1.3	1.3	0.7	1.5	1
Power train ($)	4,000	6,000 - 10,000	8,000 - 12,000	15,000 - 40,000	15,000 - 40,000	10,000 - 30,000	12,000
Power Train ($/kW)	40	60 - 100	80 - 120	150 - 400	150 - 400	100 - 300	120
Power Train (ct/km)	2.0	3 - 5	4 - 12	7.5 - 20	7.5 - 20	5 -15	6
Maintenance (ct/km)	2	2	2	5	6	4	3
Total (ct/km)	6	6 - 9	7 - 14	14 - 26	14 - 27	11 - 20	10

[1] Based on $1.00 /Gal price at the pump on a pre-tax basis

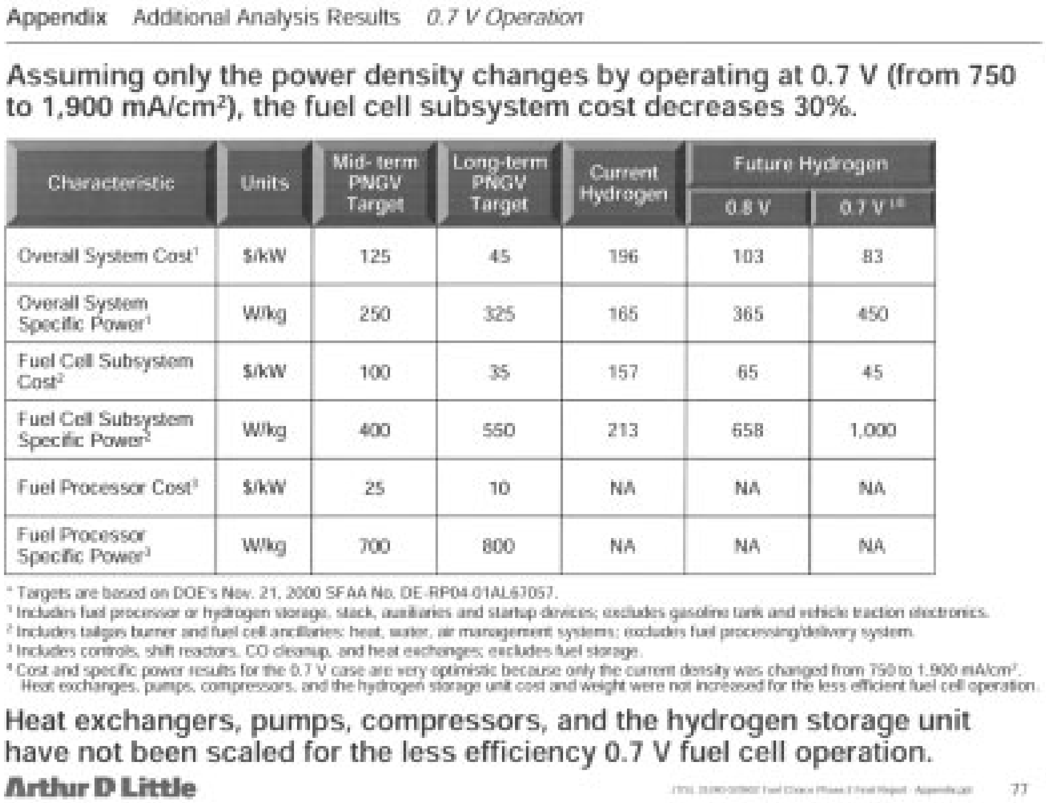
[2] Based on $0.05 per kWh power prices

Assuming there are no mass transport limitations, operating at 0.7 V rated power will result in only a 3-4%efficiency reduction at less than 20% load where a vehicle will spend most of its time.

Future Direct Hydrogen Scenario Performance Curves



* Total system efficiency includes 95% anode utilization efficiency.



Assuming only the power density changes by operating at 0.7 V (from 750 to 1,900 mA/cm^2), the fuel cell subsystem cost decreases 30%.

Characteristic	Units	Mid-term PNGV Target	Long-term PNGV Target	Current Hydrogen	Future Hydrogen	
					0.8 V	0.7 V[1,4]
Overall System Cost[1]	$/kW	125	45	196	103	83
Overall System Specific Power[1]	W/kg	250	325	165	365	450
Fuel Cell Subsystem Cost[2]	$/kW	100	35	157	65	45
Fuel Cell Subsystem Specific Power[2]	W/kg	400	550	213	658	1,000
Fuel Processor Cost[3]	$/kW	25	10	NA	NA	NA
Fuel Processor Specific Power[3]	W/kg	700	800	NA	NA	NA

[*] Targets are based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057.

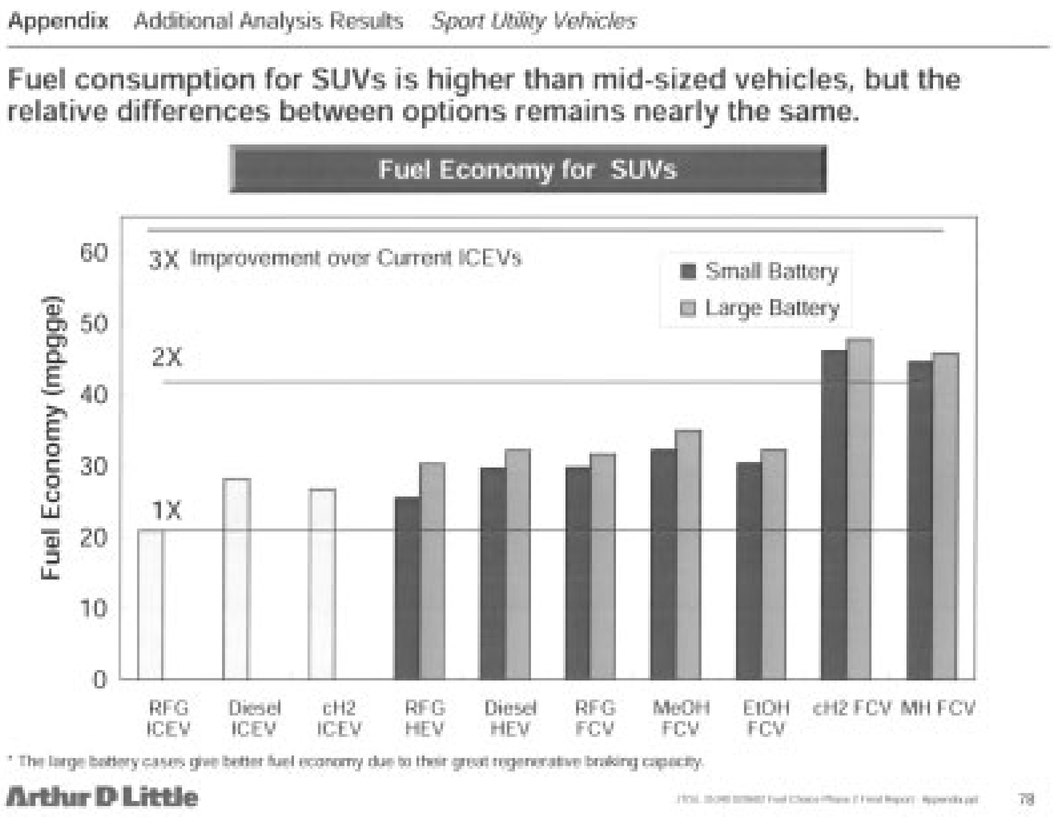
[1] Includes fuel processor or hydrogen storage, stack, auxiliaries and startup devices; excludes gasoline tank and vehicle traction electronics.

[2] Includes tailgas burner and fuel cell ancillaries: heat, water, air management systems; excludes fuel processing/delivery system.

[3] Includes controls, shift reactors, CO cleanup, and heat exchanges; excludes fuel storage.

[4] Cost and specific power results for the 0.7 V case are very optimistic because only the current density was changed from 750 to 1,900 mA/cm^2. Heat exchanges, pumps, compressors, and the hydrogen storage unit cost and weight were not increased for the less efficient fuel cell operation.

Heat exchangers, pumps, compressors, and the hydrogen storage unit have not been scaled for the less efficiency 0.7 V fuel cell operation.



Fuel consumption for SUVs is higher than mid-sized vehicles, but the relative differences between options remains nearly the same.

Fuel Economy for SUVs

* The large battery cases give better fuel economy due to their great regenerative braking capacity.

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Our projections for gasoline SUV HEV performance are in line with ANL's adjusted EERs.

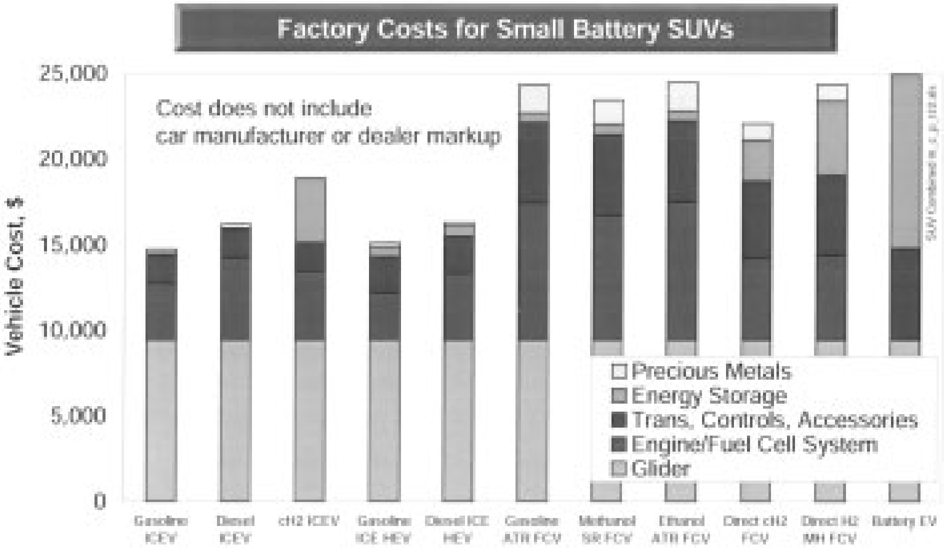
ANL Analysis of Sport Utility Gasoline HEVs[1]					
HEV Name	**Type**	**Status**	**Battery Power[2]**	**CAFÉ mpg**	**Adjusted EER**
Escape HEV	Gasoline Small SUV	Planned	35.0%	40	1.58
Durango HEV	Gasoline Full SUV	Production Prototype	33.7%	19	1.20
ADL Projections					
Large Battery HEV	Gasoline Full SUV	Projected 2010	28.7%	30.3	1.45
Small Battery HEV	Gasoline Full SUV	Projected 2010	7.1%	25.5	1.22

---

[1] Source: An, F. (ANL). "Evaluating Commercial and Prototyped HEVs", presentation at 2000 FTT Conference. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Factory costs for small battery SUVs are around 40-70% more expensive than conventional SUVs.


Factory Costs for Small Battery SUVs

Cost does not include car manufacturer or dealer markup

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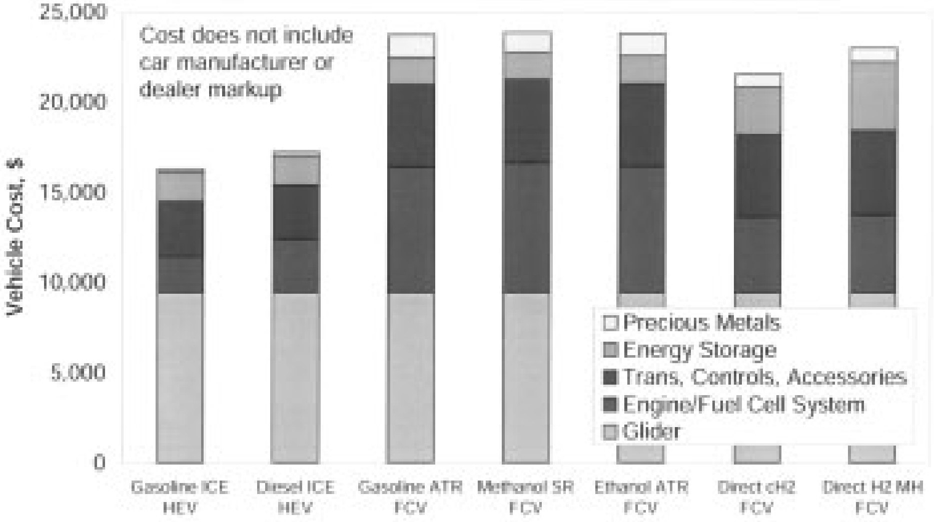
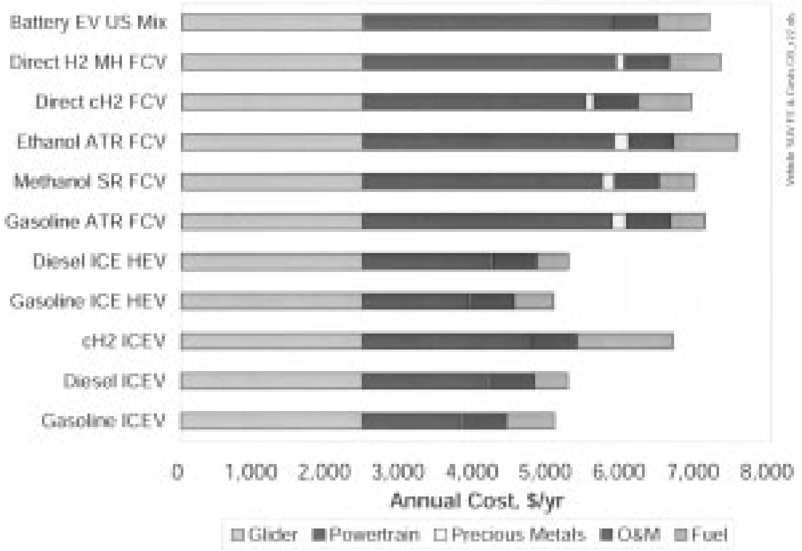
Reducing fuel cell size by increasing battery size reduces overall SU-FCV factory cost slightly.

Factory Costs for Large Battery SUVs



Annual sport utility FCV cost is around $2,000 to $3,000 more than that of conventional vehicles.

Vehicle Ownership Costs for Small Battery SUVs



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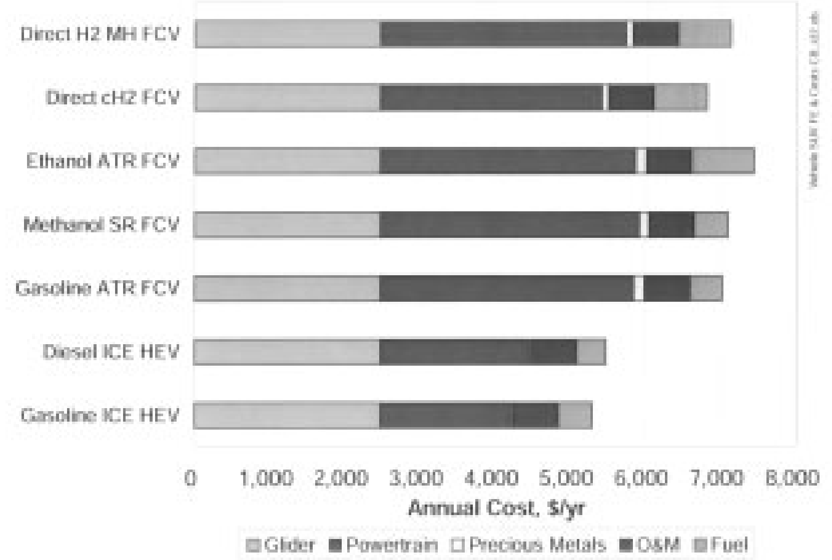
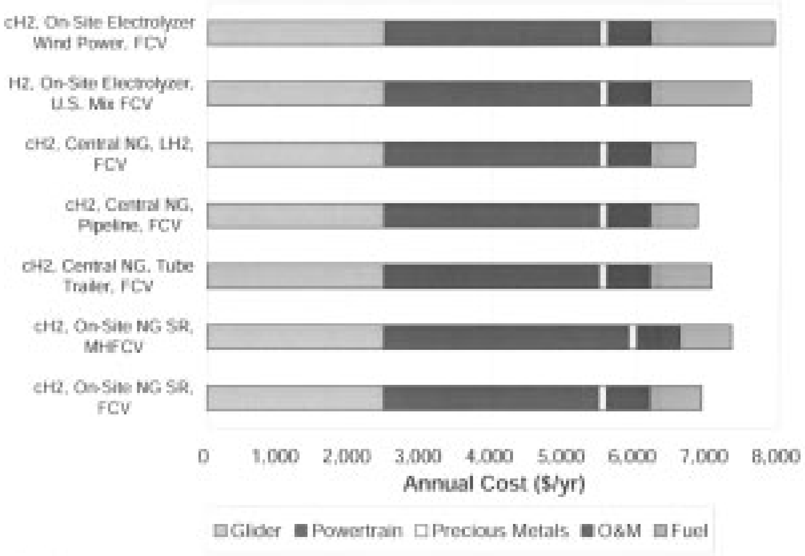
Highly hybridized SU-FCVs are only slightly less expensive under the assumptions used in this analysis.

Vehicle Ownership Costs for Large Battery SUVs



Costs for different hydrogen pathways can vary direct hydrogen FCV ownership cost by several hundred dollars per year.

Vehicle Ownership Costs for Small Battery Mid-sized Vehicles



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Outline

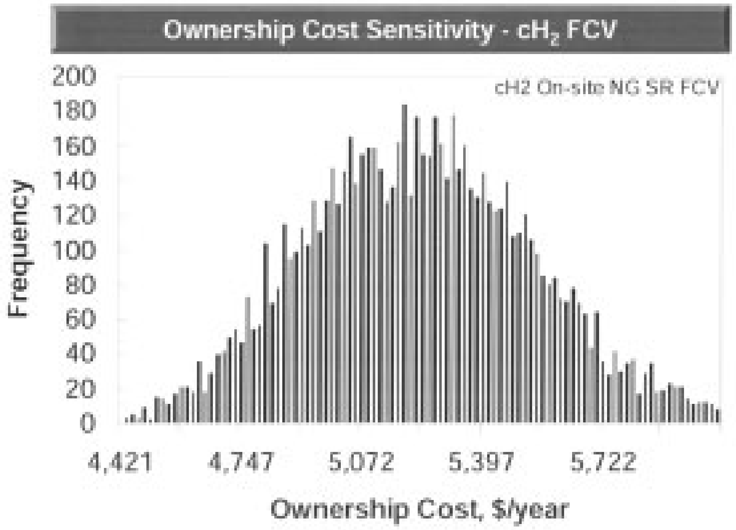
Appendix

- Glossary
- Fuel Chain Analysis Assumptions
- Vehicle Analysis Assumptions
- Platinum Loading Modeling
- Additional Analysis Results
- **Sensitivity Analysis Assumptions**
- Safety Analysis Addendum
- Target Setting
- Bibliography

Key assumptions for ownership cost sensitivity analysis:

- A Monte Carlo simulation was used to assess the uncertainty in the ownership costs for all vehicles and fuel options
  - Using Crystal Ball software, the effect of uncertainties in the ownership cost assumptions were independently varied to forecast the likely range of costs
  - Uncertainty assumptions are defined as a distribution
- Input variables for fuel price
  - Fuel cost
    - Based on historical volatility of oil and gas prices
  - Transportation and fueling station capital and operating costs
- Input variables for vehicle operation
  - Precious metals
  - Power train cost
  - Dealer markup applied to powertrain
  - Manufacturer markup applied to fuel cell, batteries, and powertrain

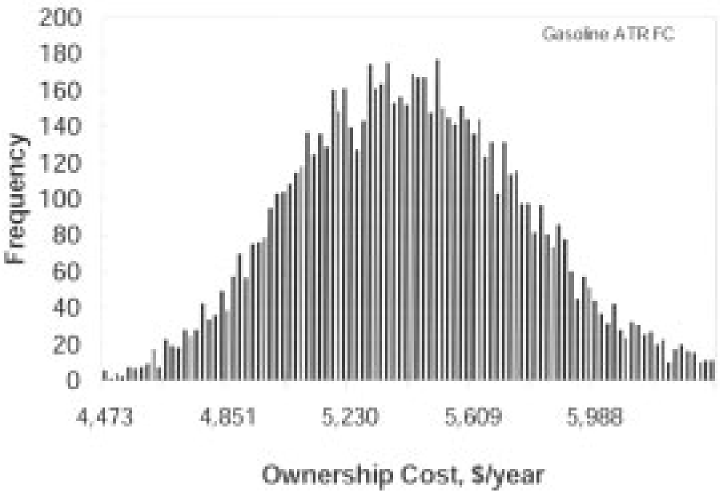
Ownership costs for direct hydrogen fuel cell vehicles (small battery mid-sized) are expected to be between $4,500 and $5,800 per year.



Monte Carlo analysis results are presented as histograms of the forecasted outcomes of the analysis.

Ownership costs for gasoline ATR fuel cell vehicles (small battery mid-sized) are expected to be slightly higher, between $4,500 and $6,200 per year.

Ownership Cost Sensitivity - Gasoline ATR FCV



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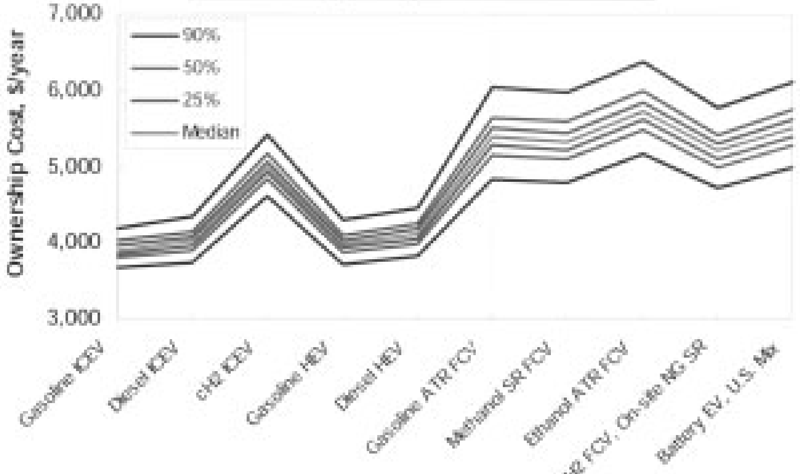
Overall, FCVs are expected to cost around $5,000-6,000 per year versus $3,500-4,500 per year for conventional and HEVs.



Sensitivity Analysis - Percentiles

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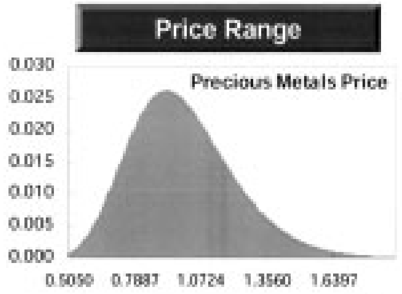
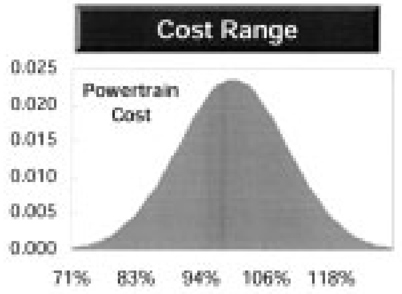
Input assumptions are represented as probability distributions.

- Input assumptions for precious metals are based on the historical volatility of platinum prices



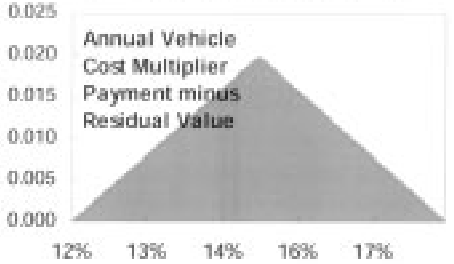
- Vehicle powertrain costs were estimated to have a 10 percent standard deviation in cost



Annual vehicle costs are based on the payments over 5 years adjusted for resale value.

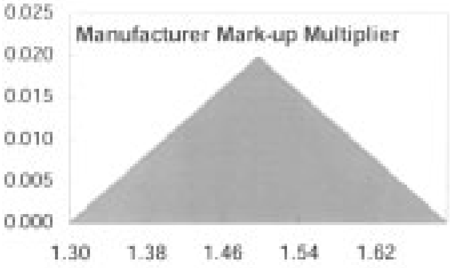
- We determined the distribution in resale values and calculated the monthly car payments, adjusted for future resale values
- The annual cost multiplier is shown here

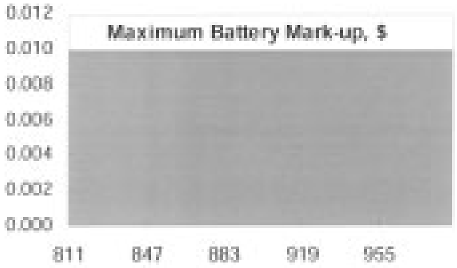
Multiplier Range

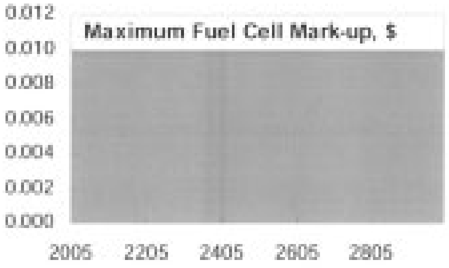


Source: Kelly Blue Book, 5 year 70,000 mile resale values for 12 most popular mid-size cars.

The effect of mark-up on powertrain components was included in the sensitivity analysis.

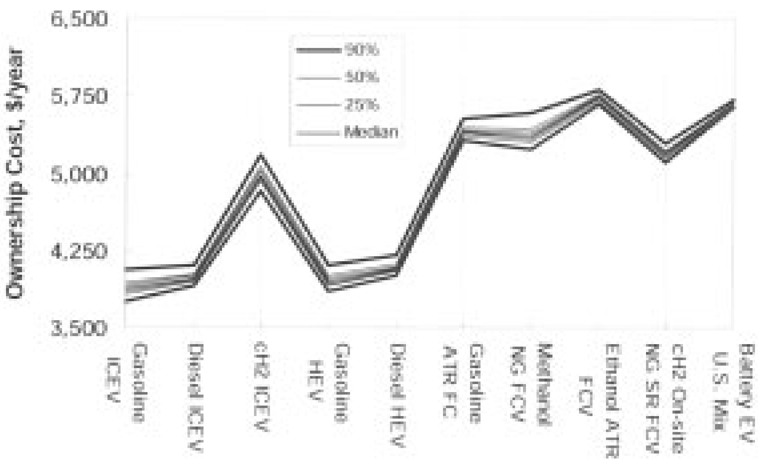






Fuel cost represents a relatively small uncertainty in ownership costs....

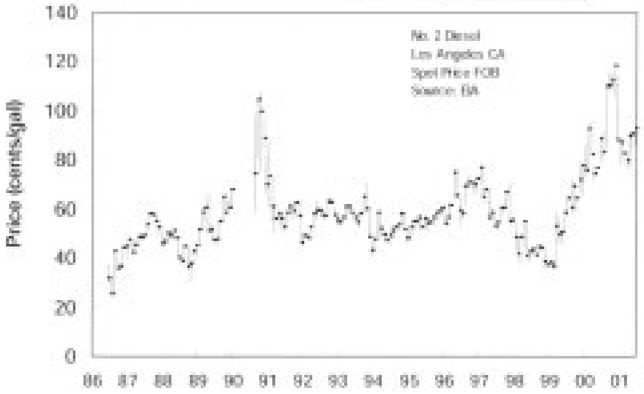
Sensitivity Analysis - Percentiles - Only Fuel Costs Varied



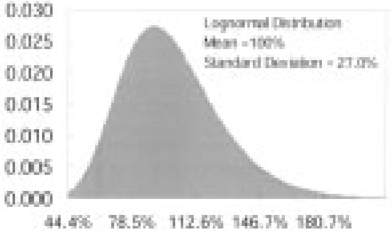
...however, the customers does not see it that way, once the vehicle purchase has been made.

The standard deviation of monthly closing prices was selected as the metric for fuel price uncertainty.

Diesel Prices, Monthly Data



Fuel Price Range



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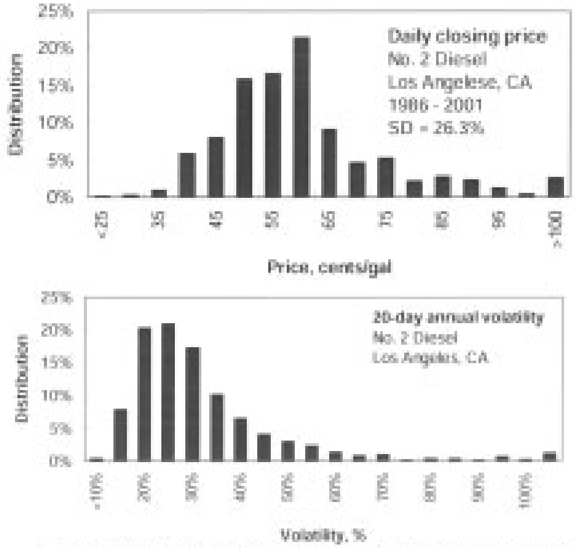
Historical volatility determines the standard deviation used in the sensitivity analysis.

Diesel Price and Volatility



- Volatility was used to characterize fluctuations in prices
  - $(\text{Volatility})^2 = \Sigma\,(ln(P_t/P_{t-1}))^2 \times D/N$

    where:

    P = daily price,

    D = trading periods per year (12)

    N=1 month
- Price data was available for more financial instruments on a monthly basis so monthly values were used to represent fuel price uncertainty
- Monthly values were similar to 20-day volatility values which are more typically used for commodity volatility analysis
- Volatility is used as the SD for a lognormal price distribution for the uncertainty analysis

Sources: Natenberg, S., "Option Pricing and Volatility", Probus, 1994; and Etzkorn, M., "Know Thy Volatility," Futures Inside Option Trading, 1996

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Monthly closing prices were collected from a variety of EIA and other publications.

Product	Data Source	Data Set
Natural Gas (Commercial)	EIA[1]	Commercial CA Sales, 1989-2001
Natural Gas (Industrial)	EIA[1]	Industrial CA Sales, 1989-2001[2]
Electricity (Comm. & Ind.)	EIA[1]	U.S. Average from all sectors, 1990-2001
Gasoline & Diesel[3]	EIA[1]	Los Angeles, CA Crude Oil Spot Prices, 1986-2001
Methanol	PCI[4]	Gulf Coast Barge Spot Prices, 1994-2001
Ethanol	Hart[5]	Midwest Spot Prices, 1992-1997

[1] Energy Information Agency, "Annual Electric Utility Report", EIA-861, http://www.eia.doe.gov

[2] Data set includes 10% of customers.

[3] Gasoline and Diesel prices are based on EIA data for crude oil and historical price spreads between petroleum products and crude oil.

[4] Petrochemical Consulting International

[5] Hart Publications, Alcohol Week

Appendix Sensitivity Analysis Assumptions *Fuel Price Uncertainty*

Historical price data was used to determine fuel price uncertainty, while 2010 prices were based on EIA and ADL projections.

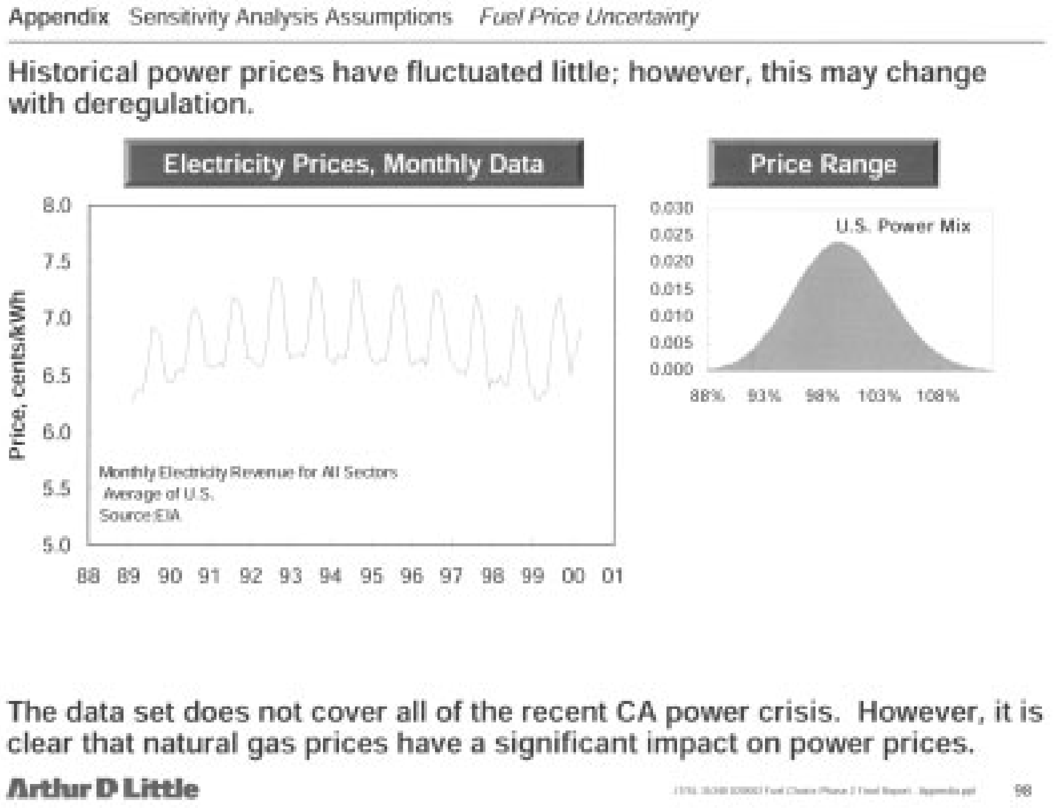
Product	Units	2010 Projection[1]	Historical Data		
			Average Price	Price Range	Volatility[2]
Natural Gas (Commercial)	$/MMBtu (HHV)	5.0	6.8	3.9-14.2	22.5%
Natural Gas (Industrial)	$/MMBtu (HHV)	3.0	4.0	2.0-11.4	30.8%
Electricity[3] (Comm. & Ind.)	c/kWh	7.0 comm. 4.0 ind.	6.7	6.2-7.4	4.2%
Gasoline[4]	$/gal	0.82	0.62	0.28-1.28	27.0%
Diesel[4]	$/gal	0.82	0.59	0.23-1.19	27.0%
Methanol	$/gal	0.41	0.56	0.25-1.55	40.5%
Ethanol	$/gal	1.15	1.20	1.01-1.54	9.1%

[1] Projected plant gate price plus delivery to fuel station. Natural gas and electricity are inputs for hydrogen production.

[2] Volatility based on historical monthly data. Volatility is used as the SD for a lognormal price distribution for uncertainty analysis.

[3] EIA historical data is electricity prices from all sectors (residential, commercial, and industrial).

[4] Projected prices are based on EIA data for crude oil and historical price spreads between petroleum products and crude oil.



Historical power prices have fluctuated little; however, this may change with deregulation.

Electricity Prices, Monthly Data

Monthly Electricity Revenue for All Sectors
Average of U.S.
Source:EIA

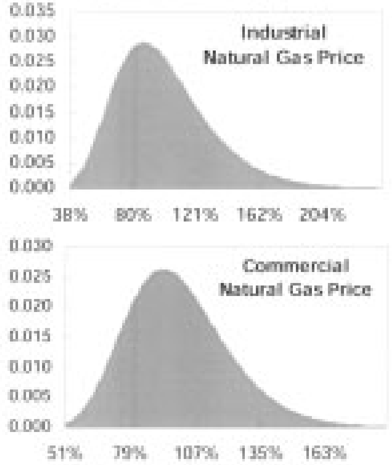
Price Range

The data set does not cover all of the recent CA power crisis. However, it is clear that natural gas prices have a significant impact on power prices.

Even before the recent rise in natural gas prices, the range in prices has been high. Prices outside California show similar volatility.

Natural Gas Prices, Monthly Data

Price Range



The cost of natural gas represents a significant part of the cost of hydrogen production.

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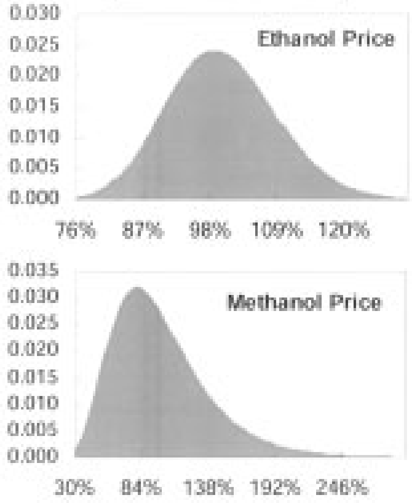
Variations in ethanol and methanol prices were also based on historical price data.

- The high volatility of methanol prices occurred because of varying degrees of production capacity in the industry over time as well as changes in the MTBE market

- It appears that ethanol will be used more prominently as an oxygenate in the future
- During the transition to greater ethanol use, the price may become more volatile

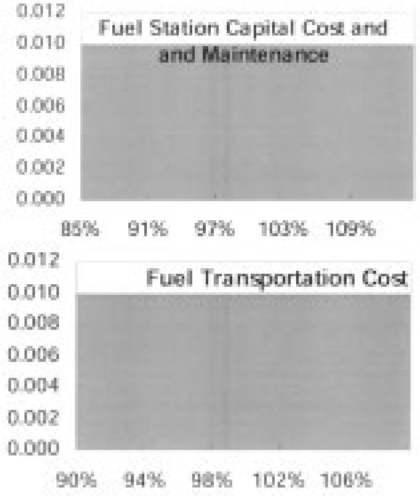
Price Range



Uncertainty in local fueling station costs and transportation costs from the central plant are also included in the sensitivity analysis.

- Fueling station costs represent a much higher share of the total cost for hydrogen, compared with other fuels

Cost Range



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Appendix

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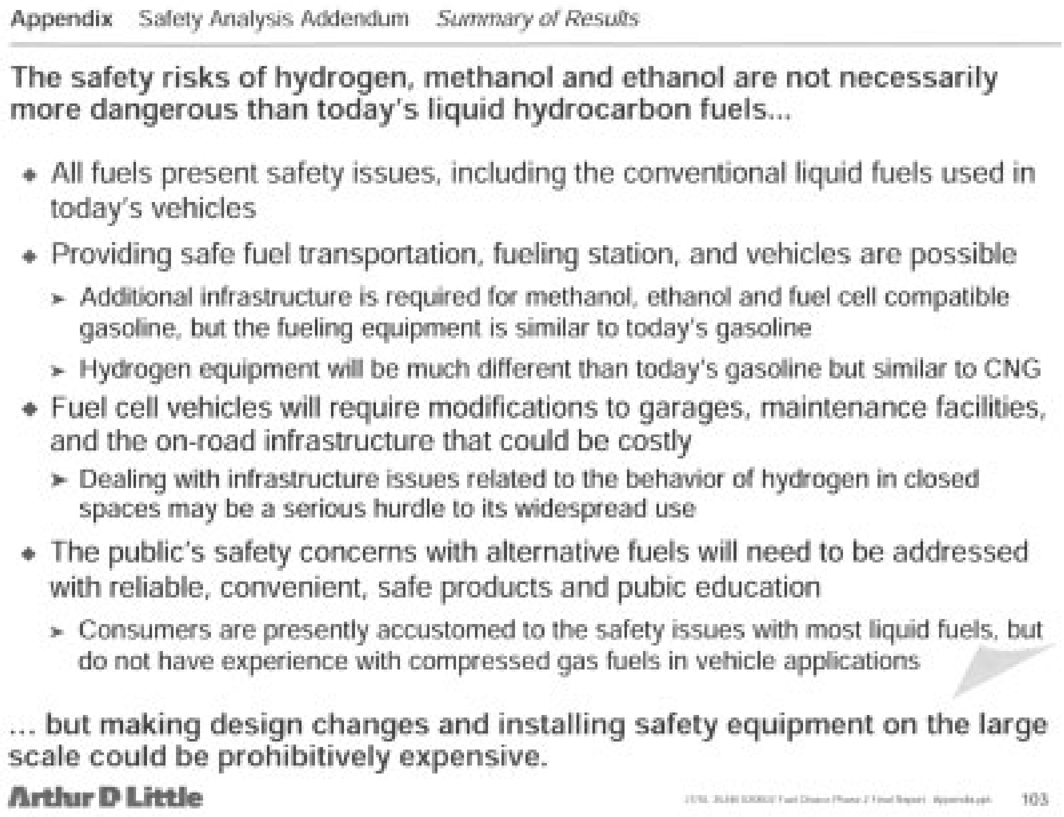
- Sensitivity Analysis Assumptions
- **Safety Analysis Addendum**
- Target Setting
- Bibliography



The safety risks of hydrogen, methanol and ethanol are not necessarily more dangerous than today's liquid hydrocarbon fuels...

- All fuels present safety issues, including the conventional liquid fuels used in today's vehicles
- Providing safe fuel transportation, fueling station, and vehicles are possible
  - Additional infrastructure is required for methanol, ethanol and fuel cell compatible gasoline, but the fueling equipment is similar to today's gasoline
  - Hydrogen equipment will be much different than today's gasoline but similar to CNG
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and the on-road infrastructure that could be costly
  - Dealing with infrastructure issues related to the behavior of hydrogen in closed spaces may be a serious hurdle to its widespread use
- The public's safety concerns with alternative fuels will need to be addressed with reliable, convenient, safe products and pubic education
  - Consumers are presently accustomed to the safety issues with most liquid fuels, but do not have experience with compressed gas fuels in vehicle applications

... but making design changes and installing safety equipment on the large scale could be prohibitively expensive.

Combustion-related safety variables include flammability and detonation, ignition energy, and gas and flame detection.

- Flammability and Detonation - fuels can only ignite when they constitute a certain range of concentrations in air
    - hydrogen has a wide flammability range
    - diesel and gasoline are flammable at low concentrations
    - hydrogen is flammable at high concentrations
- Ignition Energy - fuels require a minimum amount of energy (flame, spark, static charge) to start ignition or combustion
    - hydrogen's ignition energy is an order of magnitude lower than gasoline
- Gas and Flame Detection - fuels and their flames can pose safety risks if they are difficult to detect by sight or smell
    - undetected gas leaks of hydrogen or natural gas can cause asphyxiation if there is insufficient ventilation
    - undetected flames from hydrogen, methanol, or ethanol can cause burns and other fire hazards

National Fire Protection Association Codes (NFPA) determines electrical equipment, ventilation, equipment off-set distances, drainage, and other fire safety building requirements.

Additional safety variables, such as toxicity and storage requirements, are important to specific fuels.

- Toxicity - gasoline, diesel, and methanol contain compounds that are toxic to humans if inhaled, ingested, or absorbed through the skin
- High Pressure Storage - high pressure storage of the gaseous hydrogen and natural gas pose risk of leaks and ruptures of the vessels
  - Hydrogen poses additional risks due to its high propensity to leak and its ability to deteriorate the strength and integrity of some storage materials
- Cryogenic Storage - liquid hydrogen spills can cause cold burns if contacted with skin and boil-off poses a leak risk if not properly contained

Flammability and Detonation Safety Variables

Potential Hazards

- Combustion of liquid fuel vapors in closed spaces
- Combustion of gaseous fuel leaks from vehicle or fueling station

Applicable Codes and Standards

- NFPA 70 (National Electrical Code)
- NFPA 88A (Parking Structures), NFPA 88B (Repair Garages)
- NFPA 50A (Gaseous Hydrogen Systems at Consumer Sites)
- NFPA 52 (CNG Vehicular Fuel Systems)
- ISO/TC 197 is developing new codes, standards, and guidelines for design and operation of hydrogen fueling stations and fuel cell systems for automobiles

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Ignition Energy Safety Variables

Potential Hazards

- Combustion of gas leaks from heat or static charges
  - Operation of electronic devices (cell phones) can cause ignition
  - Common static (sliding over a car seat) is about ten times what is needed to ignite hydrogen
  - Static charges can develop during refueling of liquid fuels into ungrounded fuel containers

Applicable Codes and Standards

- NFPA 70

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Gas and Flame Detection Safety Variables

Potential Hazards

- Asphyxiation from odorless and colorless hydrogen gas leaks
- Burns from invisible hydrogen, methanol, or ethanol flames

Applicable Codes and Standards

- 49 CFR Sec. 192.625 - requires odorants in gaseous fuel pipelines to permit smell detection at concentrations of 1/5 of the lower flammability limit

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Toxicity Safety Variables

Potential Hazards

- Inhalation of toxic vapors (methanol, gasoline, diesel)
  - carcinogenic
- Ingestion of toxic liquids
  - methanol: small quantities can cause blindness/death
  - ethanol: alcohol poisoning from excessive consumption
  - all liquid fuels: leaks can contaminate water supply
- Absorption of toxic liquids (methanol, gasoline, diesel)
  - through skin contact

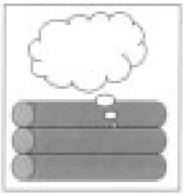
Applicable Codes and Standards

- NFPA 88A, 88B - ventilation of enclosed areas

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation

High Pressure Storage Safety Variables



Potential Hazards

- Storage vessel leak or rupture
- Hydrogen's high propensity to leak and cause embrittlement

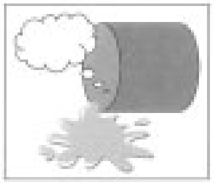
Applicable Codes and Standards

- NFPA 50A for hydrogen - building and structural setbacks
- NGV2, DOT-3A/3AA - mobile tanks testing at 5/3 service pressure, hydrostatic testing, bonfire, gunfire, drag testing
- NFPA 50A
- NFPA 52

Affected Aspects

- Fueling Stations
- Fuel Transportation
- Vehicle Configuration

Cryogenic Storage Safety Variables



Potential Hazards

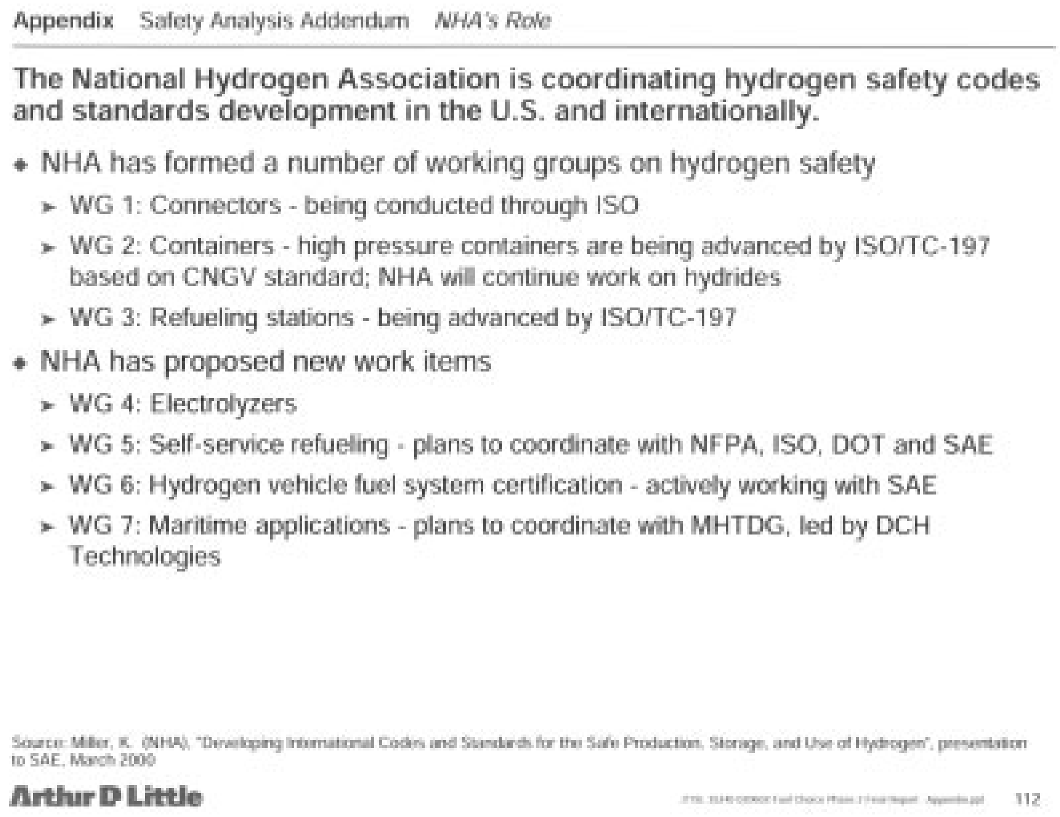
- Combustion or asphyxiation from boil-off vapors/gases
- Cold burns from leaks/spills

Applicable Codes and Standards

- NFPA 50B for liquid hydrogen - building and structural setbacks
- NFPA 70

Affected Aspects

- Fueling Stations
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration



Appendix Safety Analysis Addendum *NHA's Role*

The National Hydrogen Association is coordinating hydrogen safety codes and standards development in the U.S. and internationally.

- NHA has formed a number of working groups on hydrogen safety
  - WG 1: Connectors - being conducted through ISO
  - WG 2: Containers - high pressure containers are being advanced by ISO/TC-197 based on CNGV standard; NHA will continue work on hydrides
  - WG 3: Refueling stations - being advanced by ISO/TC-197
- NHA has proposed new work items
  - WG 4: Electrolyzers
  - WG 5: Self-service refueling - plans to coordinate with NFPA, ISO, DOT and SAE
  - WG 6: Hydrogen vehicle fuel system certification - actively working with SAE
  - WG 7: Maritime applications - plans to coordinate with MHTDG, led by DCH Technologies

Source: Miller, K. (NHA), "Developing International Codes and Standards for the Safe Production, Storage, and Use of Hydrogen", presentation to SAE, March 2000

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Details on hydrogen and other alternative fuels safety issues can be found in the following sources (page 1 of 2):

- Acurex Environmental Corporation, "Development of a Universal Methanol Fuel Formulation for use in both light and heavy-duty Vehicles, Phase I – Risk Assessment", prepared for National Renewable Energy Laboratory, November 1996A
- Acurex Environmental Corporation, "Evaluation of Fuel-Cycle Emissions on Reactivity Basis", prepared for California Air Resources Board, September 19, 1996B
- Acurex Environmental Corporation, "Maintenance Facility Modifications to Accommodate Methanol Fuel Buses", prepared with Stone & Webster Engineering for Los Angeles County Metropolitan Transportation Authority, 1993
- DeLucci, M., "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts and Cost", International Journal of Hydrogen Energy, Vol. 14, P. 81-130, 1989
- Environmental Protection Agency, "Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel", Special Report, Office of Mobile Sources, 1990
- Health Effects Institute, "Gasoline Vapor Exposure and Human Cancer: Evaluation of Existing Scientific Information and Recommendations for Future Research", 1985
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- Henry, C.P. Jr., "Electrostatic Hazards and Conductivity Additives" *Fuel Reformulation*, Jan. 1993
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- Thomas, C.E., "Hydrogen Vehicle Safety Report", prepared for DOE by the Ford Motor Company, May 1997
- Wilkman Productions, "Safety First with CNG", video produced for DOE, NREL & RTD, 1992

Outline

Appendix

- Glossary
- Fuel Chain Analysis Assumptions
- Vehicle Analysis Assumptions
- Platinum Loading Modeling
- Additional Analysis Results
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- **Target Setting**
- Bibliography

Due to the coupled nature of the subsystem efficiencies, targets should be formulated so that the total efficiency targets are met.

Fueling Station Efficiencies, %LHV	Phase II Detailed Analysis	Phase I Analysis and Targets		
		Analysis	2004	2008
Reforming	80 [1]	70-75	75-77	80
Purification	75 [1]	75-90	82-90	90
Compression	82 [2,3]	75-85	77-87	80-88
Storage & Dispensing	100 [3]	100	100	100
Total	62	NA	50-60	60-65

* Assumes power plant efficiency penalty on power requirements.

[1] Assuming the purification off-gas is used to drive the steam reforming reaction, the combined Reforming and Purification efficiency is 74%.

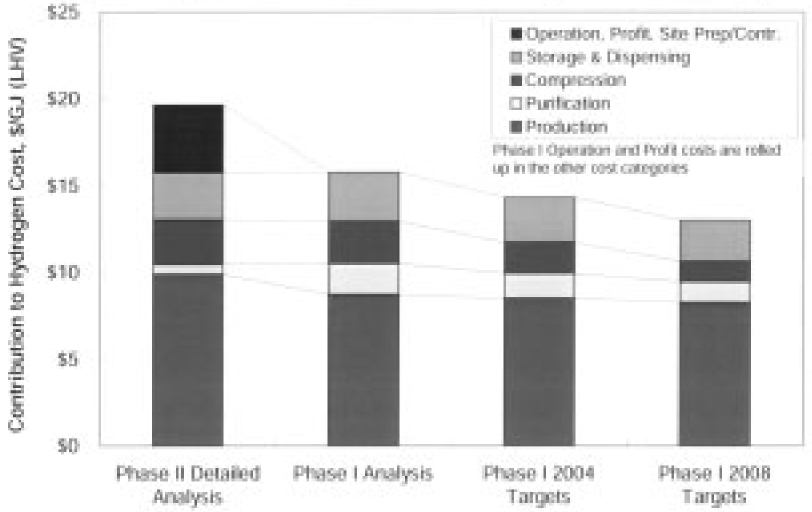
[2] Includes 3% hydrogen loss in the compressors that is recycled to the reformer burner.

[3] Based on 10 atm SR system with PSA operating at reformer outlet pressure, and 3500 psi storage to 5000 psi storage on-board the vehicle.

The efficiency targets set in Phase I still look reasonable. Given the high well-to-wheel efficiency projected for direct hydrogen FCVs, more aggressive targets aren't necessary.

Our Phase II hydrogen fuel chain cost projections significantly exceed Phase I estimates and targets primarily due to higher feedstock costs.

Comparison of On-site SR Fueling Station Costs



Annual fuel cost for direct hydrogen FCVs are on par with conventional vehicles: we refocus hydrogen production targets on risk reduction.

Assuming direct hydrogen FCVs can achieve 2.5 better fuel economy than conventional ICEVs, hydrogen cost target should be around $20/GJ, which coincides with our Phase II Results.

Hydrogen Cost, $/GJ (LHV)	Production	Purification	Compression	Storage & Dispensing	Operation, Profit, Site Prep/Contr.	Total
Phase II Analysis						
Energy Costs	$ 7.26	$ 0.12	$ 1.55	$ -		
Capital Recovery	$ 2.58	$ 0.43	$ 1.03	$ 2.64		
Maintenance Costs	$ 0.05	$ 0.01	$ 0.02	$ 0.05		
Subtotal	$ 9.89	$ 0.56	$ 2.59	$ 2.69	$ 3.91	$ 19.65
Previous Estimates						
Phase I Analysis	$ 8.73	$ 1.78	$ 2.44	$ 2.84		$ 15.79
Phase I 2004 Target	$ 8.52	$ 1.42	$ 1.78	$ 2.60		$ 14.32
Phase I 2008 Target	$ 8.28	$ 1.18	$ 1.18	$ 2.37		$ 13.02
Gasoline (Reference)						$ 8.21
Gasoline x 2.5 Fuel Economy						$ 20.52

* Based on the lower heating value of hydrogen or gasoline. There are 3600 kJ in one kWh.

We recommend delivered fuel costs targets be raised to $15-20/GJ ($0.05-0.07/kWh).

Arthur D Little

We investigated the impact of the DOE fuel cell system goals on our projected future scenarios of fuel cell system cost.

- Future gasoline and hydrogen baseline scenarios
  - ADL projected future (2010 timeframe) performance assumptions for fuel cell, balance of plant, and fuel flexible (gasoline) fuel processor or hydrogen storage
  - Based on in-house kinetic, thermodynamic, and other calculations
- DOE Goals gasoline and hydrogen scenarios
  - Assumptions changed to reflect the DOE goals published in the Annual Review and latest RFP[1]
    - current density and Pt loading
    - balance of plant component costs
    - fuel processor space velocities
  - **Other assumptions, not addressed by the RFP, were kept the same as the future baseline scenario**
  - Most DOE goals, particularly MEA Pt loading, are more aggressive than the future baseline scenario assumptions

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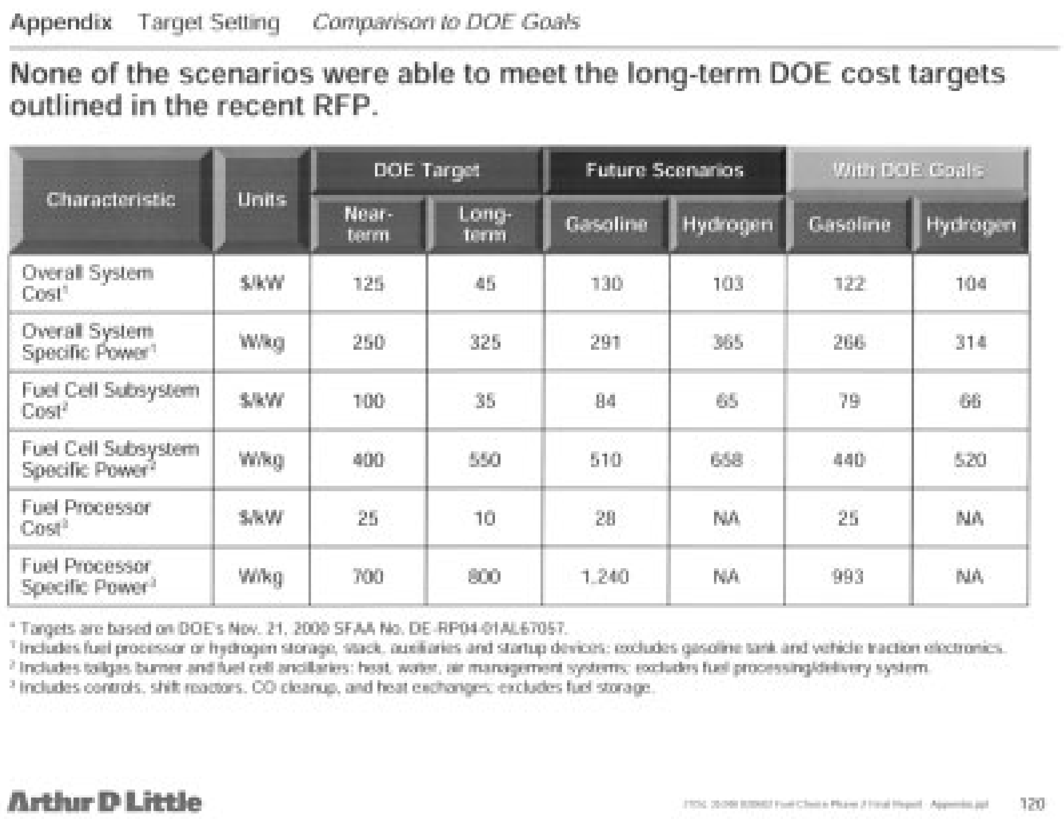
[1] Based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057, and DOE's 2000 Annual Progress Report (Oct. 2000).



None of the scenarios were able to meet the long-term DOE cost targets outlined in the recent RFP.

Characteristic	Units	DOE Target		Future Scenarios		With DOE Goals	
		Near-term	Long-term	Gasoline	Hydrogen	Gasoline	Hydrogen
Overall System Cost[1]	$/kW	125	45	130	103	122	104
Overall System Specific Power[1]	W/kg	250	325	291	365	266	314
Fuel Cell Subsystem Cost[2]	$/kW	100	35	84	65	79	66
Fuel Cell Subsystem Specific Power[2]	W/kg	400	550	510	658	440	520
Fuel Processor Cost[3]	$/kW	25	10	28	NA	25	NA
Fuel Processor Specific Power[3]	W/kg	700	800	1,240	NA	993	NA

[*] Targets are based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057.

[1] Includes fuel processor or hydrogen storage, stack, auxiliaries and startup devices; excludes gasoline tank and vehicle traction electronics.

[2] Includes tailgas burner and fuel cell ancillaries: heat, water, air management systems; excludes fuel processing/delivery system.

[3] Includes controls, shift reactors, CO cleanup, and heat exchanges; excludes fuel storage.

Arthur D Little

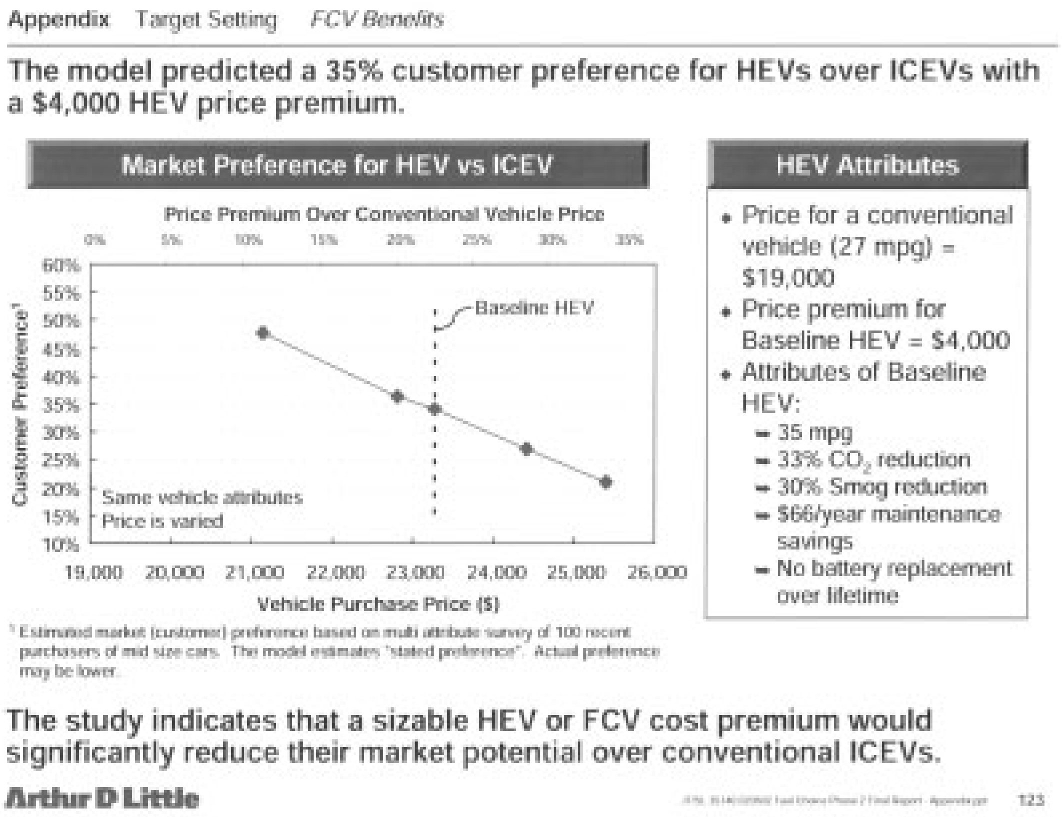
Comparing FCVs to ICEVs requires a comparison among dimensions that do not lend themselves to an "apples to apples" comparison.

	Attribute	Comments	Included in Target Setting
System Cost	*Lower Peak Power*	*FCVs will need less peak power than typical ICEVs and even HEVs*	*Yes*
	Fuel Cost	*Hydrogen FCVs and ICEVs will be equivalent, but gasoline FCVs will likely be lower than ICEVs*	*No - small affect on ownership cost*
	Maintenance	*Largely unknown for FCVs, but customers will demand same as ICEVs*	*No - not well known*
Energy and Emissions Impact	*PZEV Status*	*Additional costs will be required for ICEVs and HEVs*	*Yes*
	ZEV or Near ZEV Status	*Government incentives, credits, avoided cost of "smog check" programs for hydrogen FCVs*	*No*
	Lower GHG Emissions	*Potential government incentives for FCVs and HEVs*	*No*
	Crude Oil Independence	*Significant impact on economy (increased GDP, less defense spending) for alternative fueled vehicles*	*No*
Customer Preference	*Quiet, "Green" Vehicle*	*Pro environment, mobile office, etc. for FCVs*	*No*
	Features of Electric Drivetrains	*Genset and other capabilities for FCVs and HEVs*	*No*
	Fueling Convenience	*Convenient, quick, and fewer trips to the fueling station*	*No*

Because most energy, emissions and customer preference benefits of FCVs are difficult to monetize: we propose not to attribute a quantitative value to them in the cost target setting.

For perspective, Arthur D. Little worked previously with EPRI and Applied Decision Analysis to analyze the possible customer valuations of added HEV attributes (EPRI, 2001).

- For several HEV vehicle platforms, Applied Decision Analysis tested consumer responses
  - Survey included brief education on HEVs
  - HEV attributes are similar to FCV attributes
- Attributes include:
  - Fuel savings/fuel economy versus conventional vehicle
  - Mileage range/number of trips to the gas station versus conventional vehicle
  - Maintenance savings over conventional vehicle
  - Added HEV functionality like 110/120 volt plug in capability, heating/cooling with engine off
  - Environmental benefits versus conventional vehicle
- A model was developed to predict market share for a combination of vehicle attributes at a given vehicle price
  - We believe the indicated customer preferences represent an upper bound of the value of HEV benefits to consumers



The model predicted a 35% customer preference for HEVs over ICEVs with a $4,000 HEV price premium.

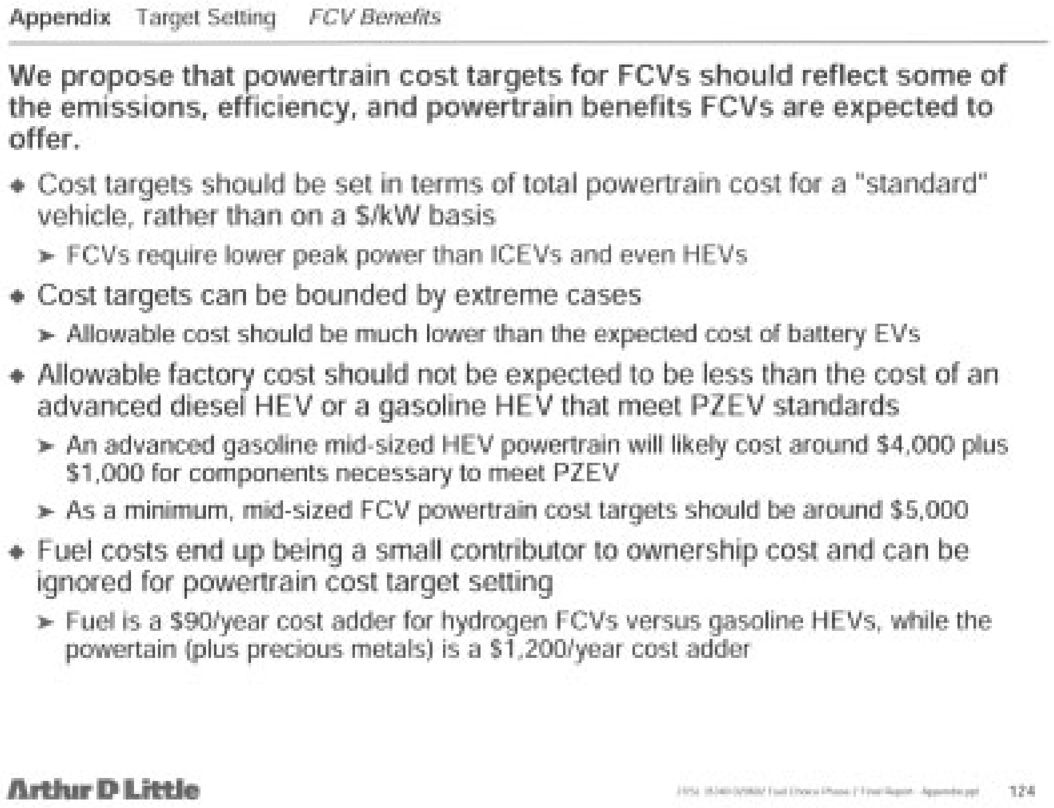
Market Preference for HEV vs ICEV

[1] Estimated market (customer) preference based on multi attribute survey of 100 recent purchasers of mid size cars. The model estimates "stated preference". Actual preference may be lower.

HEV Attributes

- Price for a conventional vehicle (27 mpg) = $19,000
- Price premium for Baseline HEV = $4,000
- Attributes of Baseline HEV:
  - 35 mpg
  - 33% CO_2 reduction
  - 30% Smog reduction
  - $66/year maintenance savings
  - No battery replacement over lifetime

The study indicates that a sizable HEV or FCV cost premium would significantly reduce their market potential over conventional ICEVs.



We propose that powertrain cost targets for FCVs should reflect some of the emissions, efficiency, and powertrain benefits FCVs are expected to offer.

- Cost targets should be set in terms of total powertrain cost for a "standard" vehicle, rather than on a $/kW basis
  - FCVs require lower peak power than ICEVs and even HEVs
- Cost targets can be bounded by extreme cases
  - Allowable cost should be much lower than the expected cost of battery EVs
- Allowable factory cost should not be expected to be less than the cost of an advanced diesel HEV or a gasoline HEV that meet PZEV standards
  - An advanced gasoline mid-sized HEV powertrain will likely cost around $4,000 plus $1,000 for components necessary to meet PZEV
  - As a minimum, mid-sized FCV powertrain cost targets should be around $5,000
- Fuel costs end up being a small contributor to ownership cost and can be ignored for powertrain cost target setting
  - Fuel is a $90/year cost adder for hydrogen FCVs versus gasoline HEVs, while the powertain (plus precious metals) is a $1,200/year cost adder

In this analysis, both gasoline and direct hydrogen vehicles are about twice the $5,000 powertrain cost target.

Powertrain Factory Costs for Selected Small Battery Mid-sized Vehicles

	Units	Gas HEV	Delta	Target	Gas FCV	cH2 FCV
Power Unit		$ 2,024	$ 500	$ 2,500	$ 6,781	$ 4,277
Trans, Controls, Accessories		$ 1,793	$ 500	$ 2,300	$ 3,268	$ 3,167
Energy Storage		$ 495	$ -	$ 500	$ 493	$ 1,691
Total		$ 4,311	$ 1,000	$ 5,300	$ 10,542	$ 9,135
Total Powertrain Size	kW	101.9		67.1	70.0	67.1
Power Unit + Energy Storage	$/kW	$ 25		$ 45	$ 104	$ 89
Trans, Controls, Accessories	$/kW	$ 18		$ 34	$ 47	$ 47
Total	$/kW	$ 42		$ 79	$ 151	$ 136
Power Unit Size	kW	92.9		58.1	61.0	58.1
Power Unit	$/kW	$ 22		$ 43	$ 111	$ 74

* Energy storage includes traction batteries and fuel tank. The hydrogen storage tank is a significant fraction of the overall cH2 FCV cost.

Designing for maximum power could reduce the direct hydrogen powertrain cost by $1,000-$1,500.

FCV market share would be enhanced with incentives and credits that value energy and emission reductions, however, such incentives are not available…

- Without incentives and credits, our ownership cost analysis results in FCVs that cost 30-50% more than gasoline ICEVs or HEVs
    - Includes vehicle, fuel, and O&M costs
- Direct hydrogen FCVs could appear attractive if all attributes are valued and incentivized
    - Effect of new fueling infrastructure on customer preference is not taken into account
    - Incentives may not be available
- Vehicles with higher cost can still achieve some market share
    - Need to assess potential market share as a function of vehicle price, fuel price, and other attributes

…limited state and local programs offer significant incentives, although the life of these programs may be limited.

Outline

Appendix

- Glossary
- Fuel Chain Analysis Assumptions
- Vehicle Analysis Assumptions
- Platinum Loading Modeling
- Additional Analysis Results
- Sensitivity Analysis Assumptions
- Safety Analysis Addendum
- Target Setting

Bibliography

Appendix Bibliography

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Note: Additional references can be found in the Safety Analysis Addendum section of the Appendix and the Module Calculations section of the Appendix Supplement.

Table of Contents

Outline

- Appendix Supplement
- Fuel Chain Analysis Approach
- Fuel Chain Performance Parameters
- Module Calculations

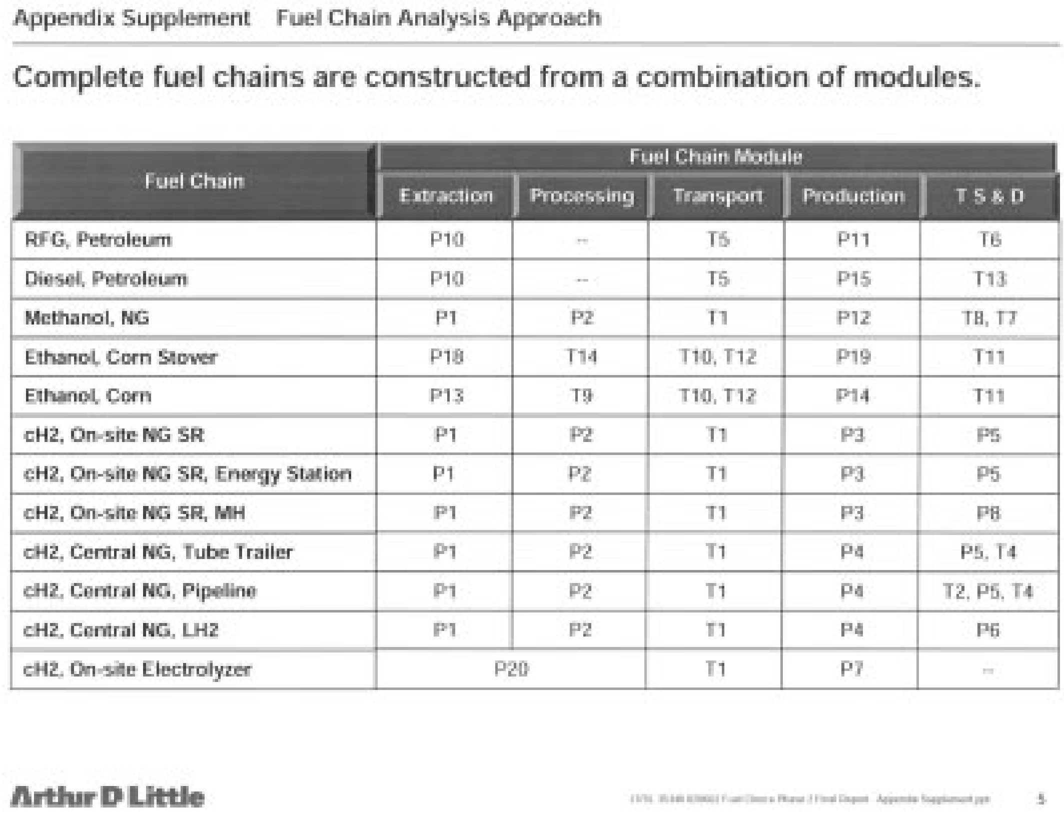
We documented the calculations and data sources for each step in the fuel chain. The analysis is sorted according to the fuel chain type.

Production and Fuel Processing	
P1	Natural Gas Extraction
P2	Natural Gas Processing
P3	Hydrogen Production
P4	Hydrogen Purification
P5	Hydrogen Compression
P6	Hydrogen Liquefaction
P7	Hydrogen Electrolysis
P8	Metal Hydride Compression
P9	Natural Gas Compression
P10	Petroleum Extraction
P11	Petroleum Refining to Gasoline
P12	Methanol from Natural Gas
P13	Corn Farming
P14	Ethanol from Corn
P15	Petroleum Refining to Diesel
P16	Biomass Chipping
P17	Biomass to Ethanol
P18	Corn Stover Collection
P19	Ethanol from Corn Stover
P20	Electricity Mix

Feedstock and Fuel Transport	
T1	Natural Gas Pipeline
T2	Hydrogen Pipeline
T3	Liquid Hydrogen Transport
T4	Hydrogen Tube Trailer
T5	Petroleum Transport
T6	Gasoline Truck
T7	Methanol Truck
T8	Methanol Marine Transport
T9	Corn Truck
T10	Ethanol Marine
T11	Ethanol Truck
T12	Ethanol Train
T13	Diesel Truck
T14	Biomass Truck

Note: Detailed fuel chain data and efficiency calculations are found in *FuelChainModules.pdf*

We assured that consistent assumptions were used for different fuels throughout the fuel chain.



Appendix Supplement Fuel Chain Analysis Approach

Complete fuel chains are constructed from a combination of modules.

Fuel Chain	Fuel Chain Module				
	Extraction	Processing	Transport	Production	T S & D
RFG, Petroleum	P10	--	T5	P11	T6
Diesel, Petroleum	P10	--	T5	P15	T13
Methanol, NG	P1	P2	T1	P12	T8, T7
Ethanol, Corn Stover	P18	T14	T10, T12	P19	T11
Ethanol, Corn	P13	T9	T10, T12	P14	T11
cH2, On-site NG SR	P1	P2	T1	P3	P5
cH2, On-site NG SR, Energy Station	P1	P2	T1	P3	P5
cH2, On-site NG SR, MH	P1	P2	T1	P3	P8
cH2, Central NG, Tube Trailer	P1	P2	T1	P4	P5, T4
cH2, Central NG, Pipeline	P1	P2	T1	P4	T2, P5, T4
cH2, Central NG, LH2	P1	P2	T1	P4	P6
cH2, On-site Electrolyzer	P20		T1	P7	--

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5

Outline

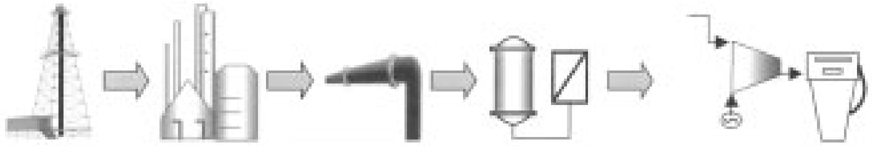
Appendix Supplement

Fuel Chain Analysis Approach

Fuel Chain Performance Parameters

Module Calculations

Compressed H_2 from natural gas, on-site steam reformer:



NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆Module P1	◆Module P2	◆Module T1	◆Module P5	◆Module P5
◆NG is the primary process fuel	◆NG is the primary process fuel	◆Pipeline Length = 1,000 miles ◆In-line compressors 50/50 mix of NG/electric power	◆300 vehicle per day station capacity ◆SMR production at 10 atm	◆H_2 compression and storage at 3600 psia ◆H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters				
◆MTE = 97%	◆MTE = 98%	◆MTE = 99+%	◆MTE = 76%	◆MTE = 93%

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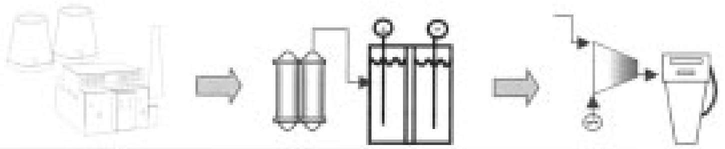
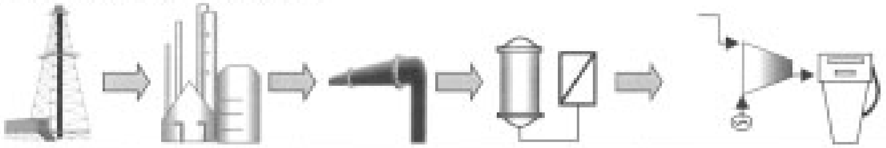
Compressed H_2 from on-site electrolyzer:



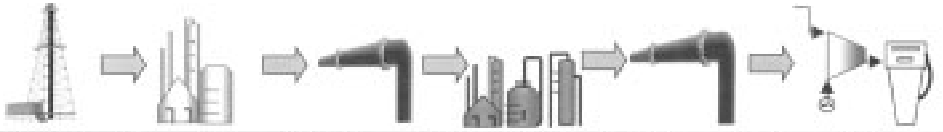
Electricity Generation	On-site H_2 Electrolyzer	T S & D
- Module P20	- Module P7	- Module P5
- Average US electricity mix. Based on GREET assumptions	- Average US power generation mix used for electricity supply	- H_2 compression and storage at 3600 psia - H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters		
- Generation Mix = 39%	- MTE = 71%	- MTE = 93%

Metal Hydride (dry) from natural gas, on-site steam reformer with low pressure on-site storage:



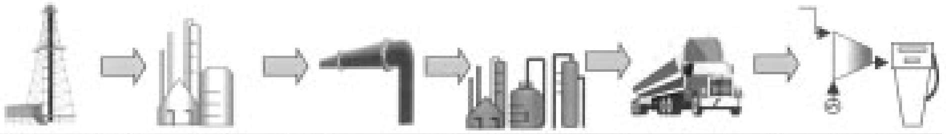
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P8
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ Low pressure H_2 on-site storage (~10atm)
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 98%

Compressed H_2 from natural gas, central steam reformer with pipeline delivery:



NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Pipeline Length = 50 miles ◆ In-line hydrogen compressors ◆ Pipeline pressure = 40 atm	◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99+%	◆ MTE = 93%

Compressed H_2 from natural gas, central steam reformer with tube-trailer delivery:



NG Extraction	NG Processing	NG Transport	Central H_2 Production	Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length – 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Assumed 50 miles one-way ◆ Tube-trailer H_2 pressure – 3600 psia	◆ Tube trailer storage ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE – 97%	◆ MTE – 98%	◆ MTE – 99+%	◆ MTE – 79%	◆ MTE – 99%	◆ MTE – 99+%

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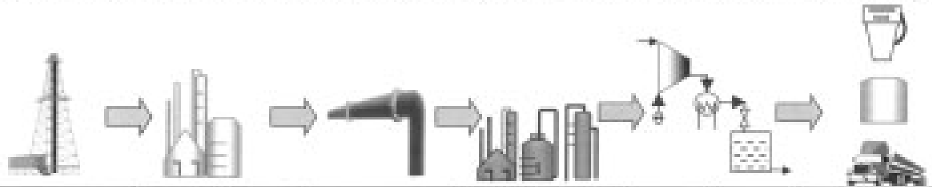
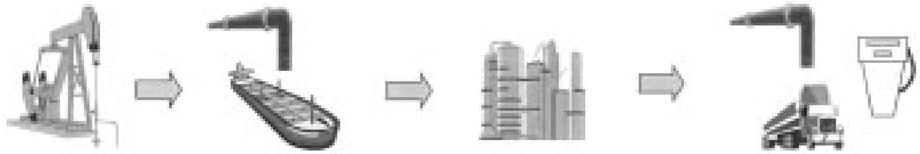
Liquid H_2 from natural gas, central steam reformer with truck delivery:

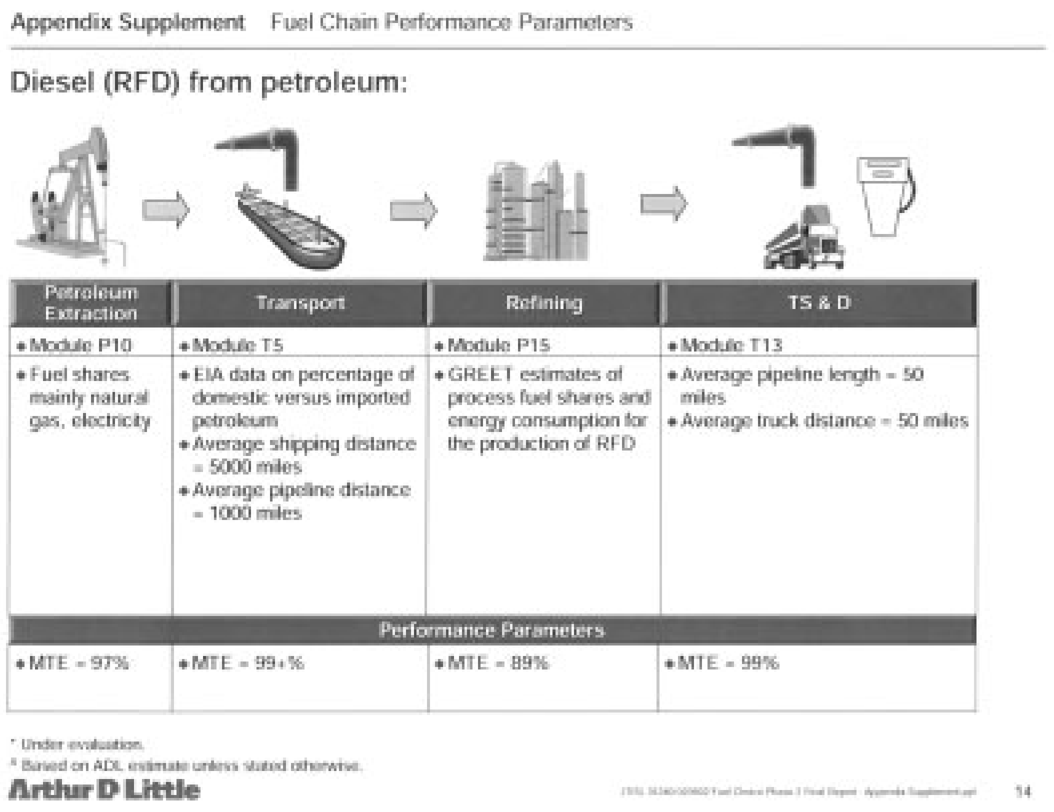


NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Liquefaction	T S & D
◆Module P1	◆Module P2	◆Module T1	◆Module P4	◆Module P6	
◆NG is the primary process fuel	◆NG is the primary process fuel	◆Pipeline Length = 1,000 miles ◆In-line compressors mix of 50/50 NG/electric	◆No steam or electricity export assumed	◆Assumed standard Linde process	◆Truck distance = 50 mi one-way ◆Truck capacity = 7800 gallons
Performance Parameters					
◆MTE = 97%	◆MTE = 98%	◆MTE = 99+%	◆MTE = 79%	◆MTE = 70%	◆MTE = 99%

Gasoline (RFG2) from petroleum:



Petroleum Extraction	Transport	Refining	TS & D
◆ Module P10	◆ Module T5	◆ Module P11	◆ Module T6
◆ Fuel shares mainly natural gas, electricity	◆ EIA data on percentage of domestic versus imported petroleum ◆ Average shipping distance = 5,000 miles ◆ Average pipeline length = 1,000 miles	◆ Fuel shares estimate based on MathPro report to CEC, 2000	◆ Average pipeline distance = 50 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 97%	◆ MTE = 99+%	◆ MTE = 84%	◆ MTE = 99%



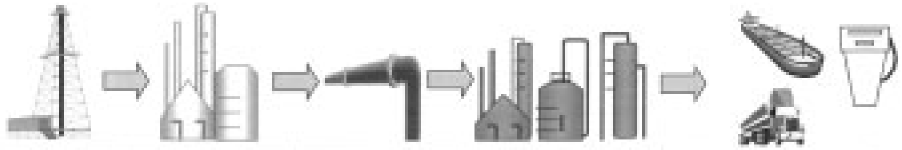
Diesel (RFD) from petroleum:

Petroleum Extraction	Transport	Refining	TS & D
- Module P10	- Module T5	- Module P15	- Module T13
- Fuel shares mainly natural gas, electricity	- EIA data on percentage of domestic versus imported petroleum - Average shipping distance = 5000 miles - Average pipeline distance = 1000 miles	- GREET estimates of process fuel shares and energy consumption for the production of RFD	- Average pipeline length = 50 miles - Average truck distance = 50 miles
Performance Parameters			
- MTE = 97%	- MTE = 99+%	- MTE = 89%	- MTE = 99%

* Under evaluation.

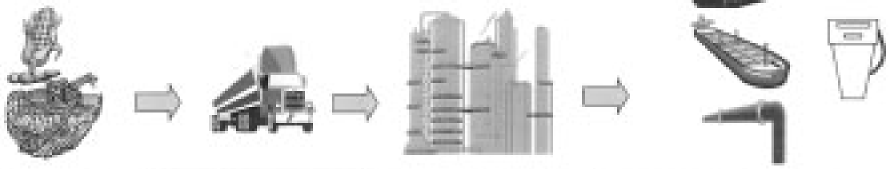
[a] Based on ADL estimate unless stated otherwise.

Methanol from remote natural gas, central production:



NG Extraction	NG Processing	NG Transport	Methanol Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P12	◆ Module T8, T7
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 25 miles ◆ In-line compressors 100% NG	◆ In-line compressors 50/50 NG/electric	◆ Average shipping distance = 7,500 miles ◆ Average truck distance = 50 miles
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 66%	◆ MTE = 97%

Ethanol from corn:



Corn Farming	Transport	Ethanol Production	T S & D
◆ Module P13, T9	◆ Module T10, T12	◆ Module P14	◆ Module T11
◆ GREET estimate of process fuel shares ◆ 17,091 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ GREET estimate of process fuel shares ◆ 4,407 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ Dry mill corn ◆ Ethanol yield = 2.65 gal/bushel ◆ 44,278 Btu/Bushel	◆ Average shipping distance = 3,500 miles ◆ Average railcar distance = 500 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 96%	◆ MTE = 98%	◆ MTE = 46%	◆ MTE = 97%

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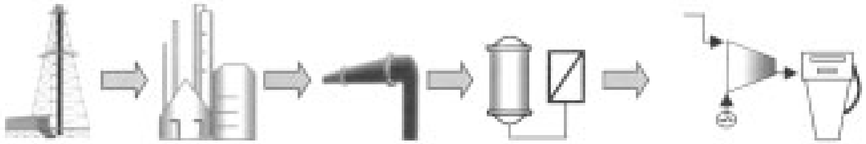
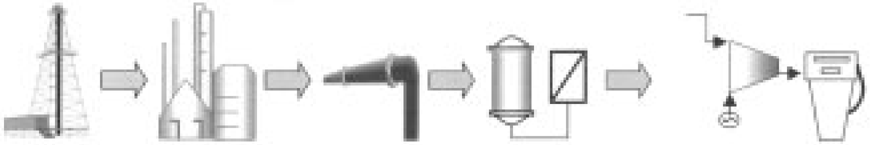
Compressed H_2 from natural gas, on-site steam reformer:



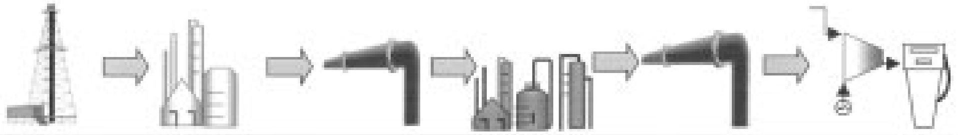
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors 50/50 mix of NG/electric power	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ H_2 compression and storage at 3600 psia ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 93%

Metal Hydride (dry) from natural gas, on-site steam reformer with low pressure on-site storage:



NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆Module P1	◆Module P2	◆Module T1	◆Module P5	◆Module P8
◆NG is the primary process fuel	◆NG is the primary process fuel	◆Pipeline Length - 1,000 miles ◆In-line compressors mix of 50/50 NG/electric	◆300 vehicle per day station capacity ◆SMR production at 10 atm	◆Low pressure H_2 on-site storage (~10atm)
Performance Parameters				
◆MTE = 97%	◆MTE = 98%	◆MTE = 99+%	◆MTE = 76%	◆MTE = 98%

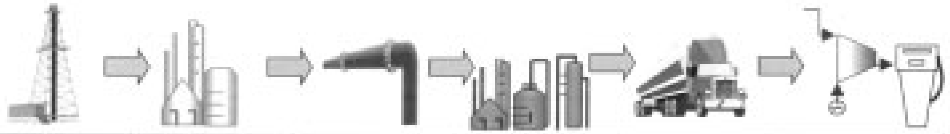
Compressed H_2 from natural gas, central steam reformer with pipeline delivery:



NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5(b)
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Pipeline Length = 50 miles ◆ In-line hydrogen compressors ◆ Pipeline pressure = 40 atm	◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99+%	◆ MTE = 93%

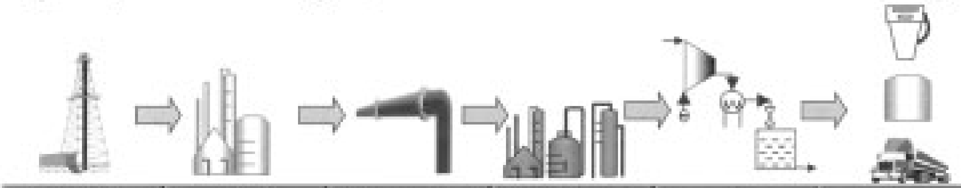
Appendix Supplement Fuel Chain Performance Parameters

Compressed H_2 from natural gas, central steam reformer with tube-trailer delivery:



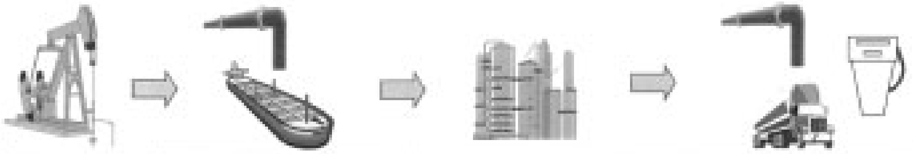
NG Extraction	NG Processing	NG Transport	Central H_2 Production	Transport	S & D
• Module P1	• Module P2	• Module T1	• Module P4	• Module T2	• Module P5(b)
• NG is the primary process fuel	• NG is the primary process fuel	• Pipeline Length = 1,000 miles • In-line compressors mix of 50/50 NG/electric	• No steam or electricity export assumed	• Assumed 50 miles one-way • Tube-trailer H_2 pressure = 3600 psia	• Tube trailer storage • H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
• MTE = 97%	• MTE = 98%	• MTE = 99+%	• MTE = 79%	• MTE = 99%	• MTE = 99+%

Liquid H_2 from natural gas, central steam reformer with truck delivery:



NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Liquefaction	T S & D
• Module P1	• Module P2	• Module T1	• Module P4	• Module P6	
• NG is the primary process fuel	• NG is the primary process fuel	• Pipeline Length = 1,000 miles • In-line compressors mix of 50/50 NG/electric	• No steam or electricity export assumed	• Assumed standard Linde process	• Truck distance = 50 mi one-way • Truck capacity = 7800 gallons
Performance Parameters					
• MTE = 97%	• MTE = 98%	• MTE = 99+%	• MTE = 79%	• MTE = 70%	• MTE = 99%

Gasoline (RFG2) from petroleum:



Petroleum Extraction	Transport	Refining	TS & D
- Module P10	- Module T5	- Module P11	- Module T6
- Fuel shares mainly natural gas, electricity	- EIA data on percentage of domestic versus imported petroleum - Average shipping distance = 5,000 miles - Average pipeline length = 1,000 miles	- MathPro	- Average pipeline distance = 50 miles - Average truck distance = 50 miles
Performance Parameters			
- MTE = 97%	- MTE = 99+%	- MTE = 84%	- MTE = 99%

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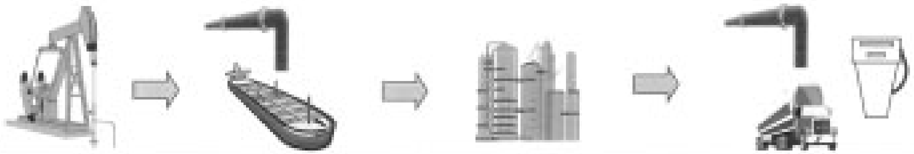
Diesel (RFD) from petroleum:

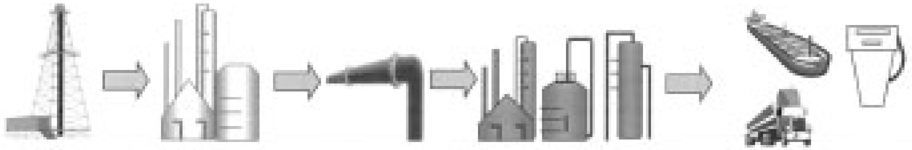


Petroleum Extraction	Transport	Refining	TS & D
• Module P10	• Module T5	• Module P15	• Module T13
• Fuel shares mainly natural gas, electricity	• EIA data on percentage of domestic versus imported petroleum • Average shipping distance = 5000 miles • Average pipeline distance = 1000 miles	• GREET estimates of process fuel shares and energy consumption for the production of RFD	• Average pipeline length = 50 miles • Average truck distance = 50 miles
Performance Parameters			
• MTE = 97%	• MTE = 99+%	• MTE = 89%	• MTE = 99%

* Under evaluation.

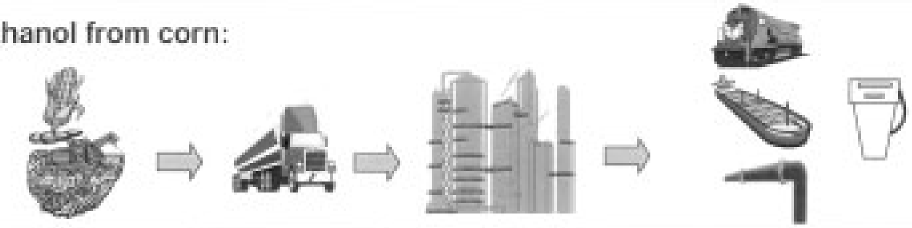
^ Based on ADL estimate unless stated otherwise.

Methanol from remote natural gas, central production:



NG Extraction	NG Processing	NG Transport	Methanol Production	T S & D
♦ Module P1	♦ Module P2	♦ Module T1	♦ Module P12	♦ Module T8, T7
♦ NG is the primary process fuel	♦ NG is the primary process fuel	♦ Pipeline Length = 25 miles ♦ In-line compressors 100% NG	♦ In-line compressors 50/50 NG/electric	♦ Average shipping distance = 7,500 miles ♦ Average truck distance = 50 miles
Performance Parameters				
♦ MTE = 97%	♦ MTE = 98%	♦ MTE = 99+%	♦ MTE = 66%	♦ MTE = 97%

Ethanol from corn:



Corn Farming	Transport	Ethanol Production	T S & D
◆ Module P13, T9	◆ Module T10, T12	◆ Module P14	◆ Module T11
◆ GREET estimate of process fuel shares ◆ 17,091 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ GREET estimate of process fuel shares ◆ 4,407 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ Dry mill corn ◆ Ethanol yield = 2.65 gal/bushel ◆ 44,278 Btu/Bushel	◆ Average shipping distance = 3,500 miles ◆ Average railcar distance = 500 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 96%	◆ MTE = 98%	◆ MTE = 46%	◆ MTE = 97%

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Outline

- **Appendix Supplement**
- Fuel Chain Analysis Approach
- Fuel Chain Performance Parameters
- Module Calculations

APPENDIX Module P1 Natural Gas Extraction

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Natural Gas	37.79	GJ, HHV	34.01	1.000	97.42%
Process Fuels					
Natural Gas	848	scf	0.830	0.02	2.38%
Petroleum	0.08	gal	0.011	0.000	0.03%
Diesel	0.29	gal	0.039	0.001	0.11%
Electricity	3.13	kWh	0.011	0.000	0.03%
Gasoline	0.09	gal	0.011	0.000	0.03%
TOTAL INPUT				1.027	100%

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	37.79	GJ, HHV	34.01	1.000
Secondary Products				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				97.4%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
Gasoline	115,500	Btu/gal
Natural Gas	1.111	HHV/LHV
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

APPENDIX Module P2 Natural Gas Processing

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Natural Gas	42.07	GJ, HHV	37.87	1.000	97.80%
Process Fuels					
Natural Gas	848	scf	0.830	0.02	2.14%
Electricity	5.56	kWh	0.020	0.001	0.05%
Gasoline	0.004	gal	0.000	0.000	0.00%
TOTAL INPUT			0.850	1.022	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	42.07	GJ, HHV	37.87	1.000
Secondary Products				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				97.8%

Input Parameters		LHV
Natural Gas	928	btu/scf
Natural Gas	1.111	HHV/LHV
Gasoline	115,500	Btu/gal
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

APPENDIX Module P4a SMR Hydrogen Production, Central

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	71.700	scf	0.070	1.26
Process Fuels				
Electricity	0.0100	kWh	3.60E-05	0.001
TOTAL INPUTS				1.261

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	1.000	lb	0.056	1.00
Secondary Products				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				79.3%

Input Parameters		LHV
Natural Gas	928	Btu/scf
	47	MJ/kg
Hydrogen	52802	Btu/lb
	119.9	MJ/kg
Conversion	0.0036	GJ/kWh
Additional Conversions		
NG	MMBtu/kg-H2	0.147
electricity	kWh/kg-H2	0.022

References

1. ADL analysis

2. "Hydrogen production Plants: Emissions and Thermal Efficiency Analysis," Contadini, J.F., Diniz, C. V., Sperling, D. and Moore, R. M., Institute of Transportation Studies, Univ. of California, Davis. 2000

APPENDIX Module P3, P4, P5 & P8 Hydrogen Production and Storage (On-Site, HYSIS Modeling)

Module Nos.		P3	P4b	P5	P8
Feedstock		Natural Gas	Natural Gas	Natural Gas	Natural Gas
Production		Local SMR	Central SMR**	Central SMR**	Local SMR
Purification		PSA			PSA
Transportation/On-site Storage		3600 psi	Tube Trailer	Pipeline	100 psi
On-board Storage		cH2	cH2	cH2	MH
On-site Energy Requirements from HYSYS					
Fuel in, kmol/hr		0.505			0.535
Fuel MW, g/mol		16.27			16.27
Fuel LHV, MJ/kg		48.83			48.83
Hydrogen out, kmol/hr		1.258	1.373	1.373	1.333
Production, kW		1.330			1.411
Purificaiton, kW		0.551			0.584
Storage, kW		6.692	3.462	8.435	1.610
Natural Gas Input	kg/hr	8.210			8.707
	MMBtu/hr, HHV	0.421			0.447
	GJ/hr, HHV	0.444			0.471
	MMBtu/hr, LHV	0.380			0.403
	GJ/hr, LHV	0.401			0.425
Power Input	kW	1.881			1.995
	GJ/hr	0.007			0.007
Hydrogen	kg/hr	2.541	2.773	2.773	2.692
	GJ/hr, HHV	0.361	0.394	0.394	0.383
	GJ/hr, LHV	0.305	0.332	0.332	0.323
Module Thermal Efficiency (Production)	%	**74.7%**	**See P4a****	**See P4a****	**74.7%**
Compression (Storage)	kW	6.692	3.462	8.435	1.610
	GJ/hr	0.02409	0.01246	0.03037	0.00580
Process Fuel Shares					
Natural Gas	%	93.5%	0.0%	0.0%	97.0%
Electricity	%	6.5%	100.0%	100.0%	3.0%
Module Thermal Efficiency (Compression)*	%	**92.7%**	**96.4%**	**91.6%**	**98.2%**

* - Central compression power is accounted for in the transportation modules

** - See Module P4a for Central SMR H2 Production

APPENDIX Module P6 Hydrogen Liquefaction

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	300.00	tons	33,429	1.00
Process Fuels				
Power Requirements* (see liquefaction tal	4,477.20	MWh	16,118	0.482
TOTAL INPUTS				1.482

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	300.00	tons	33,429	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Thermal Efficiency, GJ-output/GJ-input				67.5%

Input Parameters		LHV
Hydrogen	0.056	GJ/lb
Hydrogen-gas	lb/scf	#REF!
Conversion	GJ/kWh	0.0036

References	
1. ADL internal estimate based on " Study of Large H2 Liquefaction Proces," Matsuda and Nagami,	
Nippon Sanso Corp, (see Liquefaction Reference)	
Other Studies, MTE	
GREET, LHV	70%
ADL FORD Report, HHV	NA
NOVEM Report, HHV	81%

APPENDIX Calculation Hydrogen Liquefaction

Hydrogen Claude Cycle
General Process Description
1. Compressed to 5 MPa
2. Cooled to 80 K
3. Ortho-Para Converter - converted to 47% para hydrogen
4. Further cooling
5. Liquefied at 0.1 MPa, 20.4K, by expansion (J-T) valve

Plant Basis	300	tons/day	12500	kg/hr
Total Power Required	106.6	MW	2558	MWh
NG Compressor Efficiency	40.00%			
Assume Power Mix				
Natural Gas	50%			
Electricity	50%			
Actual Natural Gas Input to Plant	133.3	MW	0.036	MMBtu/kg
(prior to efficiency losses)				
Electricity Input	53.3	MW	4.26	kWh/kg
Total Actual Power Input	4477	MWh/day		
	14.9	MWh/ton		
	7.5	kWh/lb		

Reference: Matsuda and Nagami, Nippon Sanso Corporation, 1997, (www. enaa.or.jp/WE-NET/ronbun/1997/e5/sanso1997.html)

APPENDIX Module P7 Hydrogen from Electrolyzer

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Process Fuels				
Electricity	4.270	kWh	0.015	1.388
TOTAL INPUTS				1.388

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	0.1988	lb	0.011	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency				72.1%

Input Parameters		LHV
Hydrogen	Btu/scf	274
Hydrogen	Btu/lb	52807
Electrolysis power	kWh/Nm3	5.6
Conversion	kWh/GJ	0.0036

References	
1, Personal Communications with Stuart Energy, August 2001	
2. Teledyne Energy Systems, Specification Sheet ES-678, April 2000	
Other Studies, MTE	
ADL FORD Report, HHV	89%
NOVEM Report, HHV	80%

kWh/kg		**kWh/kg**
Electricity	Compressor	Total
47.35	2.634	50.0

APPENDIX Module P9 Natural Gas Compression

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	100.00	scf	0.098	1.00
Process Fuels				
Natural Gas	6.50	scf	0.0064	0.065
Electricity	0.75	kWh	0.0027	0.028
TOTAL INPUTS				1.093

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	100.00	scf	0.098	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				91.53%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Electricity	0.015	kWh/scf
Conversion	0.0036	GJ/kWh

References	
1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains, " ADL Report, November 1999.	
2. ADL Internal Estimations	
NG ICE efficiency	40%
Other Studies, MTE	
GREET, LHV	97%
ADL FORD Report, HHV	94%
NOVEM Report, HHV	NA

APPENDIX Module P10 Petroleum Extraction

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	6.19	bbl	35.680	1.00	96.95%
Process Fuels					
Petroleum	9.1E-01	gal	1.2E-01	3.5E-03	0.34%
Diesel	0.70	gal	0.095	2.6E-03	0.26%
Heavy Fuel Oil	0.05	gal	0.007	2.0E-04	0.02%
Natural Gas	695.0	scf	0.680	1.9E-02	1.85%
Electricity	49.60	kWh	0.179	5.0E-03	0.49%
Gasoline	0.31	gal	0.038	1.1E-03	0.10%
TOTAL INPUTS			1.1E+00	1.032	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Petroleum	6	bbl	35.680	1
Secondary Products				
TOTAL INPUTS				1.000
Module Efficiency, GJ-output/GJ-input				96.9%

Input Parameters		LHV
Natural Gas	928	btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
Gasoline	115,500	Btu/gal
Conversion	42.000	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References	
1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains," ADL Report, November 1999.	
Other Studies, MTE	
GREET, LHV	98%
ADL FORD Report, HHV	96%
NOVEM Report, HHV	96%

APPENDIX Module P11 Petroleum Refining to Gasoline

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	0.15	bbl	0.870	1.03	87.3%
Process Fuel					
Petroleum Coke	8.6E-04	tons	1.9E-02	0.02	1.9%
Diesel	0.010	gal	0.001	0.00	0.1%
Heavy Fuel Oil	0.0685	gal	0.010	0.01	1.0%
LPG	0.0157	gal	0.001	0.00	0.1%
Natural Gas	62.5	scf	0.061	0.07	6.1%
Ethanol	0.000	gal	0.000	0.00	0.0%
Electricity	1.09	kWh	0.004	0.005	0.4%
Refinery Gas	31.00	scf	0.030	0.04	3.0%
TOTAL INPUT			1.3E-01	1.185	100.0%

OUTPUTS FROM MODULE				
Primary Products:				
FRFG2	7.11	gal	0.842	1.00
Secondary Products				
None				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				84.4%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Refinery Gas	928	Btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
LPG	84,000	Btu/gal
FRFG	112,265	Btu/gal
Petroleum Coke	20,532,600	Btu/Ton
Ethanol	76,000	Btu/gal
Conversion	42.000	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References

1. ADL internal estimate based on the MathPro report - " Analysis of the refining economics of California Phase 3 RFG ," Jan 5, 2000, submitted to CEC.
2. Assume ethanol to be the long-term oxygenate

Other Studies, MTE		
GREET, LHV	86%	
ADL FORD Report, HHV	87%	RFG
NOVEM Report, HHV	88%	conventional gasoline

APPENDIX Module P12 Methanol from Natural Gas

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	93	scf	0.091	1.514
Process Fuels				
TOTAL INPUTS				1.514

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	1	gal	0.060	1.00
Secondary Products				
Steam	0	Btu	0.000	0.00
TOTAL OUTPUTS			0.060	1.000
Module Thermal Efficiency, GJ-output/GJ-input				66.05%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Methanol	57,000	Btu/gal
Steam Export	110,000	Btu/MMBtu
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References	
ADL/JT data - 68% efficiency, HHV basis	
Other Studies, MTE -- no steam credit	
ADL/JT New high cost ethanol pla	72%
ADL/JT New low cost ethanol plan	68%
GREET, LHV	70%
ADL FORD Report, HHV	62%

APPENDIX Module P13 Corn Farming

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Corn	1.00	Bushel	0.354	1.00
Process Fuels				
Energy Use (process fuels+fertilizers)	17,091	Btu	0.018	0.051
TOTAL INPUTS				1.051

OUTPUTS FROM MODULE				
Primary Products:				
Corn	1.00	Bushel	0.354	1.00
Secondary Products				
TOTAL OUTPUTS			0.354	1.000
Module Efficiency, GJ-output/GJ-input				95.2%

Input Parameters		LHV
Ethanol yield	2.65	gal/bushel
Ethanol	76,000	Btu/gal
Corn Weight	56	lb/bushel
Corn Heat Value	6,000.00	Btu/lb
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

REFERENCES	
1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug, 1999	
ANL Transportation TEchnology R&D CEnter, ANL/ESD-39	
2. ADI estimates	
Other Studies, MTE	
GREET, LHV	17,091 Btu/Bushel
ADL FORD Report, HHV	87%
NOVEM Report, HHV	87%

APPENDIX Module P14 Ethanol from Corn

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Corn	2.65	gal/bushel		
Other Inputs				
Natural Gas	17,414	mmBtu/gal	12,689	16,733
Coal	17,414		12,689	16,733
Electricity	2.10	kWh/gal	7,165	7,559
Total			32,543	41,026
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal		76,000
Secondary Products				
DDGS, 21% protein				
Total				

INPUT PARAMETERS		
Corn	Btu/lb LHV	6000
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Natural Gas	Btu/scfLHV	970
	lb/100scf	4.52
	kg/100scf	2.05
Steam Boiler Efficiency	Btu/Btu	80%
Electricity Conversion	Btu elec/kWh	3412
Power Plant Efficiency		38%
Energy Conversion	kJ/Btu	1.055
Portion of energy from electricity production available as steam	%	50%

References

1. 2.65 gal/bushel refers to yield in ProForma Cost Summary Report for Dry-Mill corn ethanol plant
2. 34,828 Btu at 80% boiler efficiency to produce 27,862 Btu of needed steam (carbonbalance.xls)
3. 2.1 kWh/gal is electricity input required in ProForma Cost Summary Report (carbonbalance.xls)

4. NREL, 1999. Environmental Life Cycle Implications of Fuel Oxygenate Production from California Biomass

Notes

1. Natural Gas is energy required for steam production. Cogen assumes that steam is also obtained from waste heat in electricity production
2. Other fuels could be used to provide steam energy. Assumption is that boiler efficiency is constant at 80%. Assumption also used in NREL, 1999 (see below).
3. Allocation of input energy to co-product not accounted for here
4. Cogen operation assumes that 50% of electricity-produced steam is used in production and therefore avoids additional natural gas
5. A good figure of merit for energy consumption is an on-site energy consumption value for steam production and a value for electricity consumption. Some other studies and the GREET model, however, use a combined figure of merit. As a result, we converted our electricity consumption into a Btu elec/gal value so the total could be input into GREET. In order to compare with other studies, this number must be converted to Btu thermal/gal. This conversion results in a value of 54,000 Btu/gal not including cogen, which is within the range of the other studies that also neglected cogen: approximately 48,000 Btu/gal to 63,000 Btu/gal.

Table of other studies' results is in CornModule.xls

APPENDIX Module P15 Petroleum Refining to RFD

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	0.16	bbl	0.922	1.050	93.55%
Process Fuel					
Petroleum Coke	1.9E-04	tons	4.0E-03	0.005	0.41%
Heavy Fuel Oil	0.0198	gal	0.003	0.003	0.30%
LPG	0.0047	gal	0.000	0.000	0.04%
Natural Gas	25.2	scf	0.025	0.028	2.50%
Electricity	0.31	kWh	0.001	0.001	0.11%
Refinery Gas	31.00	scf	0.030	0.035	3.08%
TOTAL INPUTS			6.3E-02	1.122	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Diesel	6.50	gal	0.878	1
Secondary Products				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				89.1%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Refinery Gas	928	btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
LPG	84,000	Btu/gal
Gasoline	115,500	Btu/gal
Petroleum Coke	20,532,600	Btu/Ton
Conversion	42	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References

1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains," ADL Report, November 1999.

Comments	
Other Studies, MTE	
GRFFT, LHV	87%
ADL FORD Report, HHV	97% conventional diesel
NOVEM Report, HHV	95%

APPENDIX Module P16 Biomass Chipping

		Units	LHV, Btu	LHV, kJ	J/MJprimary product delivered
INPUTS TO MODULE					
Input Fuel					
Forest Material	1	BDT	17,000,000	17,935,000	1,000,000
Other Inputs					
Diesel	2.20	gal/BDT	281,600	297,088	16,565
Total			17,281,600		1,016,565
OUTPUTS FROM MODULE					
Primary Products:					
Forest Material	1	BDT	17,000,000	17,935,000	1,000,000
Secondary Products					
None					
Total					1,000,000
Module Efficiency, GJ-output/GJ-input					98.4%

INPUT PARAMETERS		
Forest Material	Btu/dry-lb	8500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Chipping fuel requirement within range of various studies
2. QLG Feasibility Study suggests a cost of $30-40/BDT for this processing

COMMENTS

1. Assume heat rate of biomass is 8500 Btu/dry lb

Other Studies, MTE		
GREET, LHV	234,770	gal diesel/BDT
ADL FORD Report, HHV		
NOVEM Report, HHV		

APPENDIX Module P17 Ethanol from Biomass

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Forest Material	77.70	gal/BDT		
Other Inputs				
Natural Gas	0	mmBtu/gal	0	0
Electricity	0.00	kWh/gal	0	0
Diesel	1.45	gal/1000 gal	186	176
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal	76,000	72,038
Secondary Products				
Electricity	2.066	kWh thermal/gal	18,594	17,625
Total				

INPUT PARAMETERS		
Biomass	Btu/dry-lb	8500
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
Electricity Conversion	Btu/kWh	9000
Energy Conversion	kJ/Btu	1.055

References

1. ProForma Cost Summary Report (calculations in carbonbalance.xls)
2. Scenario is midterm ethanol plant using lignin to provide energy inputs (Case 34)

Notes

1. Lignin by-product is combusted to produce steam and excess electricity
2 No marketable co-products are accounted for

APPENDIX Module P18 Corn Stover Collection

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Corn Stover	1.00	BDT	15.071	1.00
Process Fuels				
Diesel	181,665	Btu/BDT	0.192	0.013
TOTAL INPUTS				1.013

OUTPUTS FROM MODULE				
Primary Products:				
Corn Stover	1.00	BDT	15.071	1.00
Secondary Products				
None				
TOTAL OUTPUTS			15.071	1.000
Module Thermal Efficiency, GJ-output/GJ-input				98.7%

Input Parameters		LHV
Ethanol yield	95.00	gal/bdt
Ethanol	76,000	Btu/gal
Corn Weight	56	wet lb/bushel
Corn Stover/Corn ratio	1	lb/lb
Corn Stover Heat Value	7,143	Btu/dry-lb
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

REFERENCES

1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug, 1999
ANL Transportation TEchnology R&D CEnter, ANL/ESD-39
2. Corn Stover Collection Project, DOE, 1998.
3. Estimate that diesel required for collecting stover is equal to one quarter of diesel used in corn farming (17091Btu/Bushel)

Other Studies, MTE		
GREET, LHV	17,091	Btu/Bushel
ADL FORD Report, HHV	87%	
NOVEM Report, HHV	87%	

APPENDIX Module P19 Ethanol from Corn Stover

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Corn Stover	95.00	gal/BDT		
Other Inputs				
Natural Gas	0	mmBtu/gal	0	0
Electricity	0.00	kWh/gal	0	0
Diesel	1.45	gal/1000 gal	186	176
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal	76,000	72,038
Secondary Products				
Electricity	2.066	kWh thermal/gal	18,594	17,625
Total				

INPUT PARAMETERS		
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
Electricity Conversion	Btu/kWh	9000
Energy Conversion	kJ/Btu	1.055

References

1. Energy inputs based on ethanol from woody material in ProForma Cost Summary Report (calculations in carbonbalance.xls)
2. Scenario is midterm ethanol plant using lignin to provide energy inputs (Case 34)
3. Yield of 95 gal/ton based on 80gal/wet ton estimated as initial corn stover yields in DOE Corn Stover Collection Project, 1998. With mature conversion technology, up to 130 gal/ton

Notes

4. Lignin by-product is combusted to produce steam and excess electricity

APPENDIX Module P20 Electricity Generation

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Coal	5,341	Btu	5.6E-03	1.57	54.0%
Oil	79	Btu	8.3E-05	0.02	0.8%
Natural Gas	1,309	Btu	1.4E-03	0.38	21.1%
Nuclear	1,244	Btu	1.3E-03	0.36	12.4%
Other (Renewables)	998	Btu	1.1E-03	0.29	11.7%
TOTAL INPUT	8,971	Btu	9.5E-03	2.6E+00	

OUTPUTS FROM MODULE				
Primary Products:				
Electricity	1.00	kWh	0.004	1.00
Secondary Products				
None				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				38.03%

Input Parameters		LHV
Conversion	3,412	Btu/kWh
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ
U.S. AVERAGE ELECTRICITY GENERATION MIX		
REF: GREET		
	%	Efficiency, %
COAL	54.0%	34.5%
OIL	0.8%	34.5%
NG*	21.1%	55.0%
NUCLEAR	12.4%	34.0%
OTHER**	11.7%	40.0%
* -- Combined Cycle		
** -- Industry Experience		

APPENDIX Module T1 Natural Gas Transport, Pipeline

		Units	LHV, GJ	GJ/GJ primary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	1,000,000	scf	9.79E+02	1.000
Process Fuel				
Electric + NG Power	1.575	hp-hr/MMscf	4.23F+00	0.004
TOTAL INPUTS				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	1,000,000	scf	9.79E+02	1.000
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				99.57%

INPUT PARAMETERS		
Natural Gas		
Heating Value, LHV	Btu/scf	928
Pipeline Length	mi	1000
NG Compressor ICE efficiency factor		0.4
Use Factor	hp-hr/MMscf/mi	1.575
Conversion Factor	kJ/hp-hr	2684.52

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	97.0%
ADL FORD Report, HHV	97.4%
NOVEM Report, HHV	99.9%

APPENDIX Module T2 Hydrogen Transport, Pipeline

		Units	LHV, GJ	GJ/GJ primary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	1,000,000	scf	2.89E+02	1
Process Fuel				
NG + Electricity	1.75	GJ	1.75E+00	0.01
TOTAL INPUTS				1.01
OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	1,000,000	scf	2.89E+02	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.00
Module Efficiency, GJ-output/GJ-input				99.40%

INPUT PARAMETERS		
Hydrogen		
Heating Value, LHV	Btu/scf	274
	Btu/lb	52802
	lb/MMscf	5189.20
	kg/MMscf	2353.38
NG, LHV	Btu/scf	928
Process Fuel Power	GJ/MMscf	1
Natural Gas ICE Efficiency Factor		0.4
NG Process Fuel Share		50%
Electricity Process Fuel Share		50%
Conversion	GJ/MMBtu	1.055
Conversion	GJ/kWh	0.0036
Additional Conversions		
NG Process Fuel Share	MMBtu/kg	0.0005
Electricity Process Fuel Share	kWh/kg	0.0591

REFERENCES

1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains, NOVEM, November 1999.

COMMENTS

1. Assumes a 50-mile long pipeline

Other Studies, MTE		
GREET, LHV	97.0%	
ADL FORD Report, HHV	99.2%	100-mile pipeline
NOVEM Report, HHV	99.6%	50-mile pipeline

APPENDIX Module T3 Liquid HydrogenTransport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
LH2	3,370	kg/truck	407	1.00
Process Fuels				
Diesel	18.18	gal (round trip)	2.5	0.01
TOTAL INPUTS				1.01

OUTPUTS FROM MODULE				
Primary Products:				
LH2	7,800	gal	407	1.00
Secondary Products				
None				
Total				1
Module Efficiency, GJ-output/GJ-input				99.4%

INPUT PARAMETERS		
Average Truck	mi/gal	5.5
Average One-way Trip Distance	mi	50
LH2	Btu/gal LHV	30100
	lb/gal	0.580
	kg/gal	0.263
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

References	
1. Refinement of Selected Fuel-Cycle Emissions Analyses, Vol. 1 Final Report, Dec 2000	
Prepared for CARB and SCAQMD, FR-00-101 by Arthur D. Little	
2. Hydrogen - The Coming Fuel, Linde Presentation, INTERTECH, Nice, France, May 2001	
Other Studies, MTE	
GREET, LHV	95.0%
NOVEM Report, HHV	99.9%

APPENDIX Module T4 Hydrogen Transport, Tube Trailer

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	530	kg	68.01	1.000
Process Fuel				
NG + Electricity (Ref:2)	#REF!	kWh	#REF!	#REF!
Diesel	20.00	gal (round trip)	2.7	0.040
TOTAL INPUTS				#REF!

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	530	kg	68.01	1.000
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				#REF!

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Compression Power	kWh/GJ	#REF!
Hydrogen	kg/kmol	2.016
	Btu/lb, LHV	52802
	Btu/kg, LHV	116428
	Btu/kmol, LHV	245198
	GJ/kmol, LHV	0.2587
	Btu/scf, LHV	274
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24
conversion	kWh/GJ	278

References	
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996	
Prepared for CARB by Acurex Environmental	
2. ADL see tab "H2 Compression"	
Other Studies, MTE	
GREET, LHV	97.0%

APPENDIX Calculation Hydrogen Tube Trailer Compression

Central SMR, Hydrogen Compression for Tube Trailer				
Hydrogen	1.373	kmol/hr	0.337	GJ/hr
Required Power	6.84	kW_e	0.025	GJ/hr
Power Shares				
Natural Gas	50%			
Electric Motor Efficiencv	95%			
IC Engine Efficiency	40%	LHV		
Actual Input Compressor	8.6	kW_{th}	0.011	MMBtu/kg
Electricity	50%			
	3.25	kW	1.174	kWh/kg
Input				
Compressor	11.8	kW	0.042	GJ/hr
	35.061	kWh/GJ		
Output				
Hydrogen	1.26	kmol/hr	0.337	GJ/hr
Module Thermal Efficiency			88.8%	

APPENDIX Module T5 Petroleum Transport, Pipeline&Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Petroleum	142,500	DWT	6.11E+06	1.000
Other Inputs				
Bunker Fuel	513,000	kg (round trip)	2.18E+04	0.004
Diesel	2,243	gal	3.03E+02	0.000
Total				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Petroleum	142,500	DWT	6.11E+06	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.64%

INPUT PARAMETERS		
Petroleum		
Density	kg/gal	3.2
Energy Content	Btu/gal, LHV	130000
	Btu/kg	40625
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	1000
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996	
Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	99.5%

APPENDIX Module T6 Gasoline Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Gasoline	7,800	gal	950	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Gasoline	7,800	gal	950	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Gasoline	Btu/gal LHV	115500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	98.5%

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APPENDIX **Module T7** Methanol Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Methanol	7,800	gal	469	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.006
Total				1.006

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	7,800	gal	469	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.4%

INPUT PARAMETERS		
Average Truck	mi/gal	5
Average One-way Trip Distance	mi	50
Methanol	Btu/gal LHV	57000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

References

1. Refinement of Selected Fuel-Cycle Emissions Analyses, Vol. 1 Final Report, Dec 2000
Prepared for CARB and SCAQMD, FR-00-101 by Arthur D. Little

APPENDIX Module T8 Methanol Transport, Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Methanol	142,500	DWT	6.07E+06	1.0000
Other Inputs				
Bunker Fuel	3,847,500	kg (round trip)	1.64E+05	0.0270
Diesel	2,243	gal (In-port)	3.03E+02	0.0000
Total				1.0270

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	142,500	DWT	6.07E+06	1.0000
Secondary Products				
None				
Total				1.0000
Module Efficiency, GJ-output/GJ-input				97.37%

INPUT PARAMETERS		
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	7500
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24
Methanol		
	Btu/gal LHV	57000
	lb/gal	6.60
	kg/gal	2.996

REFERENCES
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis. Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environemntal

APPENDIX Module T9 Corn Transport, Truck

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Input Fuel				
Corn-ethanol	1.00	Bushel	0.414	1.00
Other Inputs				
Energy Use forTransportation	4,897	Btu	0.005	0.012
Total				1.012

OUTPUTS FROM MODULE				
Primary Products:				
Corn-ethanol	1.00	Bushel	0.414	1.00
Secondary Products				
None				
Total			0.414	1.000
Module Efficiency, GJ-output/GJ-input				98.8%

Input Parameters		LHV
Ethanol yield	2.65	gal/bushel
Ethanol	76,000	Btu/gal
Corn	7,000	Btu/lb
	56	lb/Bushel
Corn Stover	95	gal/BDT
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References
1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug. 1999 ANL Transportation TEchnology R&D CEnter, ANL/ESD-39 2. ADL industry experience

APPENDIX Module T10 Ethanol Transport, Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Ethanol	142,500	DWT	3.61E+06	1.000
Other Inputs				
Bunker Fuel	1,795,500	kg (round trip)	7.64E+04	0.021
Diesel	2,243	gal (In-port)	3.03E+02	0.000
Total				1.021

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	142,500	DWT	3.61E+06	1.000
Secondary Products				
None				
Total				1.000
Module Efficiency, GJ-output/GJ-input				97.92%

INPUT PARAMETERS		
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	3500
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24
Ethanol		
Heat Content	Btu/gal LHV	76000
Density	kg/gal	2.996
Density	lb/gal	6.60

REFERENCES
1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environemntal

APPENDIX Module T11 Ethanol Transport, Truck

		Units	LHV, GJ	J/MJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Ethanol	7,800	gal	625	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.004
Total				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	7,800	gal	625	1.000
Secondary Products				
Total				1.000
Module Thermal Efficiency				99.6%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Ethanol	Btu/gal, LHV	76000
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environmental

APPENDIX Module T12 Ethanol Transport, Train

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Ethanol	30,000	gal	2,405	1.000
Process Fuels				
Diesel	53.57	gal (round trip)	/	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	30,000	gal	2,405	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Train Fuel Usage	gal/1000-ton mi	87.2
Average One-way Trip Distance	mi	500
Ethanol Transport Factor		0.25
Ethanol	Btu/gal, LHV	76000
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environmental

APPENDIX Module T13 Diesel Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Diesel	7,800	gal	1,053	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Diesel	7,800	gal	1,053	1.000
Secondary Products				
None				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Gasoline	Btu/gal LHV	115500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	98.6%

APPENDIX Module T14 Biomass Transport, Truck

		Units	LHV, Btu	LHV, kJ	J/MJprimary product delivered
INPUTS TO MODULE					
Input Fuel					
Forest Material (chipped)	1	BDT	8,500	8,968	1,000,000
Other Inputs					
Diesel	1.57	gal/BDT (round trip)	201,143	212,206	23,663,866
Total			209,643		24,663,866
OUTPUTS FROM MODULE					
Primary Products:					
Ethanol	1	BDT	8,500	8,968	1,000,000
Secondary Products					
None					
Total					1,000,000

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	4
One way distance for 40 mill gal plant	mi/trip	44
Mass	BDT/truck	14
Forest Material (chipped)	Btu/BDT, LHV	8500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Costs and Benefits of Biomass-to-Ethanol Production Industry in California,
ADL report to the California Energy Commission, March 2001

COMMENTS

1. One way distance is the average travel for a plant with biomass available within a 50 mile radius
Reference 1 estimated costs at $9-19/BDT ($50-55 per hour of travel)

Other Studies, MTE		
GREET, LHV	308,400	gal diesel/BDT

APPENDIX Module T19 Power Transmission

		Units	LHV, GJ	GJ/GJ, primary fuel
INPUTS TO MODULE				
Input Fuel				
Electriciy	1.0000	kWh	0.004	1.053
Other Inputs				
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Electricity	0.9500	kWh	0.003	1.000
Secondary Products				
None				
Total				
Module Thermal Efficiency				95.00%

INPUT PARAMETERS		
Conversion	GJ/kWh	0.0036

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