Argonne
NATIONAL LABORATORY

ANL-07/09

Examining Hydrogen Transitions

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

ANL-07/09

Examining Hydrogen Transitions

---

by
S. Plotkin
Energy Systems Division, Argonne National Laboratory

for
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy

February 2007

Acknowledgments

Steve Plotkin, Argonne National Laboratory, was the author of this report.

Jeff Dowd, DOE's Office of Energy Efficiency and Renewable Energy (EERE) sponsored this work and provided substantial advice and assistance in its completion.

The author is grateful to the considerable assistance granted (including report review), and advice given, by David Greene and Paul Leiby of Oak Ridge National Laboratory, Chip Friley of Brookhaven National Laboratory, and Frances Wood of OnLocation, Inc. He is also grateful to others who reviewed the draft report:

- Dan Loughlin, U.S. Environmental Protection Agency
- Dan Mears, Technology Insights
- Charles Forsberg, Oak Ridge National Laboratory
- Charles Drummond, Rodney Geisbrecht, and Michael Reed, National Energy Technology Laboratory
- Sonia Yeh, North Carolina University
- Joan Ogden, University of California, Davis

Table of Contents

EXECUTIVE SUMMARY

This report describes the results of an effort to identify key analytic issues associated with modeling a transition to hydrogen as a fuel for light duty vehicles, and using insights gained from this effort to suggest ways to improve ongoing modeling efforts. The study reported on here examined multiple hydrogen scenarios reported in the literature, identified modeling issues associated with those scenario analyses, and examined three DOE-sponsored hydrogen transition models in the context of those modeling issues.

The three hydrogen transition models are HyTrans (contractor: Oak Ridge National Laboratory), MARKAL/DOE[*] (Brookhaven National Laboratory), and NEMS-H2 (OnLocation, Inc). The goals of these models are (1) to help DOE improve its R&D effort by identifying key technology and other roadblocks to a transition and testing its technical program goals to determine whether they are likely to lead to the market success of hydrogen technologies, (2) to evaluate alternative policies to promote a transition, and (3) to estimate the costs and benefits of alternative pathways to hydrogen development.

The reviewed hydrogen scenario analyses offer a number of insights that could prove useful to modelers and policy analysts seeking to understand a hydrogen transition. Key examples are:

- A transition to hydrogen will look different across and even within regions, because of varying feedstock availability and costs, large differences in traffic densities, and other factors, and may require different strategies to promote the transition.
- At the beginning of a transition, neither the fuel cell vehicles nor the hydrogen fuels are likely to be cost-competitive with conventional gasoline or diesel vehicles, also, potential purchasers of hydrogen vehicles and developers of infrastructure must deal with the risk that the transition will be delayed, reducing the value of their investments.
- A hydrogen transportation system's ability to use renewable electricity (with hydrogen produced by electrolysis) has been promoted as a means to greatly reduce greenhouse gas emissions from transportation. However, using such electricity to back out fossil electricity (or to power electric vehicles) will be far more effective at reducing such emissions. For the foreseeable future (until there is excess availability of renewable electricity) generating hydrogen might not be considered an optimum use of renewable electricity.
- Hydrogen vehicles will be competing with a moving target – conventionally-fueled vehicles will improve also, especially given the stimulus of competing with hydrogen vehicles; and hydrogen's effect in reducing gasoline demand could cause gasoline prices to drop, making ICE-powered vehicles more competitive.

---

[*] MARKAL is a widely used model. For example, the Environmental Protection Agency runs a separate version, as do a number of international groups.

On the other hand, the literature reviewed in this effort offers only modest guidance to the DOE and the federal government in helping to design a hydrogen R&D program and formulate a strategy to accelerate hydrogen use in the light-duty vehicle fuel market. Most of the analyses reported on in the reviewed literature basically skirt the issue of the transition and look at the "end state' where hydrogen has become a primary vehicle fuel. Further, most of the analyses simply postulate a degree of hydrogen penetration rather than attempting to derive the level of penetration based on an evaluation of the factors that might drive hydrogen into the LDV fuels market. In some cases, stock models are used to develop estimated levels of hydrogen penetration, but these depend on assumptions about sales of new hydrogen vehicles. Finally, most of the analyses do not describe any attempt to conduct a "reality check" on the scenarios, e.g. to test whether the assumed rates of development would strain industry resources or whether key investment "actors" are likely to be able to satisfy standard investment goals.[*] Thus, these analyses offer little insight about what conditions and/or policies would actually lead to their postulated levels of hydrogen penetration. Note that the literature review "closed" in August, 2005, and substantial new literature on hydrogen transitions has become available since then, but is not reported on here.

This report develops a list of characteristics for an "ideal" hydrogen transition model (section 5), and examines the characteristics of NEMS-H2, HyTrans, and MARKAL/DOE in the context of that list (section 6). However, it would be unwise for us to judge one model as "better" or "worse" than the others for most characteristics because there are important tradeoffs to be made in selecting each aspect of model design. This is especially the case because many aspects of the behavior of potential investors in a hydrogen transition (including vehicle purchasers) and the characteristics of a future hydrogen economy are poorly understood, so that investments in model complexity and disaggregation risk outrunning the state of knowledge. Hopefully, however, this examination of hydrogen scenarios and modeling issues will offer some useful insights for both the transition modelers and for DOE analysts hoping to better understand whether and how to create a successful transition to hydrogen in the transport sector.

A crucial issue facing those trying to model a hydrogen transition is the difficulty of credibly modeling the behavior of the key actors who will drive a transition to hydrogen – consumers who may purchase hydrogen vehicles; vehicle manufacturers; fuel suppliers; and fuel distributors (and the investors needed to bankroll the latter three actors). Modeling consumer behavior is a difficult enterprise in the best of circumstances, but modeling potential buyers of hydrogen vehicles is further complicated by large uncertainties in how such vehicles will behave and how much they will cost, as well as by consumers' lack of experience with a hydrogen refueling system. Modeling the vehicle and fuels industry is complicated by the large uncertainties in future market conditions these industries will face and in the costs and performance of vehicle and fuel production technologies. In particular, the fact that industry faces a "chicken or egg" problem – without developed markets, investors in vehicle manufacturing, hydrogen

---

[*] Presumably, some of these analyses explicitly considered restraints on maximum growth rates, but generally these were not documented in the literature reviewed here.

production, and fuel distribution all have to rely on each other to follow through on their investments in order to have any chance at success—greatly complicates modeling industry behavior. Modelers also have to make difficult decisions about the level of aggregation they will use to describe the various actors and the behavioral rules they will apply to them.

Although there are large differences in the three models examined in this report, all three have chosen to model consumers and investors as if they had a clear view of future fuel prices and other conditions – either “perfect foresight” where they “see” the scenario of the future that has been input to the model, or “myopia,” which assumes that the future will look like the present (or that current trends will continue). In this approach, in any particular model run, uncertainty in future conditions may be partially accounted for by increasing the financial hurdle rates that investors will apply to potential investments in vehicle manufacturing plants and other infrastructure, but is otherwise not taken into accounted. On the other hand, multiple runs of the models, with varying future conditions, may be able to give insight about the effect on industry behavior of uncertainty in future market conditions and technology costs and performance. However, to our knowledge the modelers have not yet defined a method to translate the results of multiple runs into an account of likely behavior under uncertainty.

Another important modeling issue is choosing the level of detail applied to the potential “actors” in a transition, as well as to the overall environment they face. For example, the MARKAL/DOE model treats the energy sector as if it were a single actor, whereas HYTRANS examines actions of individual vehicle manufacturing plants – though these plants are basically all the same. And NEMS divides the U.S. into census regions, whereas HYTRANS recognizes 3 geographic regions within the U.S. (and further subdivides each region into 3 levels of density of demand), and MARKAL/DOE treats the U.S. as a single region.[*] Although it is simplistic to assume that “more detail is better” – more detail increases model complexity and cost, and demands data and an understanding of the behavior of individual actors that may not be available – the level of disaggregation in a model will affect the types of polices that can be examined. For example, highly aggregated models may not be able to model targeted incentives (e.g., incentives aimed only at small distributors or at low density rural areas), although these might be critical in developing an affordable incentive program for a hydrogen transition.

There are a number of additional modeling and analysis issues that will require careful consideration in future efforts to model a hydrogen transition. These include:

1. <u>Choosing a Reference Case</u>. Replacement of our massive gasoline infrastructure probably makes sense only in the context of a world where there is severe danger of energy security emergencies and/or environmental calamity. There is a tendency in scenario analyses to use standard Reference Cases such as that in the Energy Information Administration’s Annual Energy Outlook. However, these

---

[*] Both DOE and EPA are in the process of regionalizing their versions of MARKAL.

Reference Cases generally describe a world of relative energy and environmental stability, and are inappropriate for use in a hydrogen scenario analysis.

2. Using Optimization Models. HyTrans and MARKAL/DOE use optimization to develop least cost scenarios. A key issue here is how well these scenarios are likely to relate to what actually will unfold in the real world, and whether the testing of policies under optimization routines will identify the same "best" policies that would be identified if one could realistically model real world behavior.
3. Capturing Learning Effects. The process of cost reduction through "learning" effects is complex and imperfectly understood, but it is likely that existing modeling efforts to track learning will miss some important nuances. Technological learning is not perfectly shared among industry actors, and crosses national boundaries because so many of the industry "actors" are multinational corporations likely to be developing hydrogen infrastructure in several places at once. Current models tend to look only within national boundaries and only at the industry as a single entity. What makes this particularly important in modeling a hydrogen transition is that early hydrogen vehicle and other elements of the infrastructure will likely be extremely expensive, and cost reductions through learning are absolutely crucial to successfully navigating a transition.

It is true of all models that proper interpretation of their results demands a good understanding of the model's structure and limitations – and this is certainly true for hydrogen transition models, perhaps more so than for other transport models. Modelers of hydrogen transition are going to have to be careful to make it clear to model users and policymakers how their model's character and assumptions affect modeling results, and they should be careful in describing what types of analyses the model is good for, and what types might be problematic. And hopefully the modelers will play a role in designing (or at least reviewing) analyses using their model and in interpreting model results.

There are strong differences among the three models examined here, and among these and other transition models currently under development. It is inevitable that there will also be strong differences among the *results* obtained from these models. Previous studies by the Energy Modeling Forum (at Stanford University) and others have proven very useful in providing comparative analyses of complex models, and duplicating such efforts with hydrogen transition models could prove equally useful.

It is useful to point out that it is not possible at this time to identify a "best" approach to modeling a transition to hydrogen, even if the model users and their analytic requirements can be clearly defined. Methods for analyzing long-term energy market transitions are in their infancy. Also, a transition to hydrogen fuel cell vehicles will rely on novel technology with which consumers have no experience and whose costs and performance are highly uncertain. There is limited experience in analyzing futures under this level of uncertainty.

1. INTRODUCTION

U.S. interest in a transition from oil-based liquid fuels to hydrogen as the energy source for vehicles has grown markedly during the past decade because of a convergence of factors:

- Growing U.S. oil imports coupled with the growing market power of OPEC (hydrogen could be produced largely or completely from domestic resources);
- An emerging concern that world conventional oil production may peak during the first half of this century, requiring the production of massive quantities of replacement fuels;
- Growing concerns about climate change (hydrogen use in vehicles produces no greenhouse gases, although hydrogen *production* would do so unless the feedstocks were renewable or otherwise carbon neutral).
- Substantial technical progress in the development of PEM fuel cells and other technologies needed for a transition to hydrogen use in transportation.

U.S. and worldwide research efforts in hydrogen development have grown rapidly. In his 2003 State of the Union address, President Bush announced the Hydrogen Fuel Initiative, a $1.2 billion commitment over 5 years to accelerate hydrogen-related research to move hydrogen vehicles from the laboratory to the showroom.

A substantial focus of the U.S. program is on how to manage a transition to hydrogen. As part of this effort, DOE's Office of Energy Efficiency and Renewable Energy (EERE) is sponsoring the enhancement of existing models (e.g. NEMS and MARKAL) and the development of new models (e.g., HYTRANS) that will examine this transition under alternative scenarios of future economic and social conditions and assist EERE in:

- Enhancing its R&D effort by improving DOE's understanding of the relative importance of a range of technological and other roadblocks to a successful transition (thus improving its ability to properly allocate R&D funds);
- Calculating the costs and benefits of alternative pathways to hydrogen development; and
- Evaluating alternative policies to promote a transition.

Box 1 briefly describes the three models.

Box 1. NEMS, MARKAL, and HyTrans

The National Energy Modeling System, or NEMS, is a general equilibrium energy-economic model of U.S. energy markets. NEMS contains modules representing each of the fuel supply markets, conversion sectors, and end use consumption sectors of the energy system, plus macroeconomic and international modules; these modules communicate through an integrating module rather than directly with each other. NEMS reaches a solution by calling each supply, conversion, and end-use demand module in sequence until the delivered prices of energy and the quantities demanded have converged, achieving an economic equilibrium of supply and demand in the consuming sectors. NEMS's time horizon is 25 years. Depending on sector, NEMS divides the nation into 3 to 20 regions, with electricity production divided into 13 regions.

The MARKet ALlocation model, or MARKAL, is a dynamic linear programming model of the national economy that contains a database of several hundred processes covering the lifecycle for energy and materials flows in the economic system. The model calculates a least cost characterization of the flows and processes of the economy under constraints such as the maximum introduction rate of new technologies, availability of resources, environmental goals for energy use and emissions, and so forth, assuming perfect foresight where future constraints are taken into account in current investment decisions and all time periods are simultaneously optimized. MARKAL is a long-term model with a time horizon on the order of 40-80 years.

The Hydrogen Transition Model, or HyTrans, is a market equilibrium simulation model that solves for the decisions of hydrogen producers and retailers, vehicle manufacturers and consumers. It is a dynamic, multi-period optimization model that represents the behavior of the various actors in the hydrogen energy system as rational economic agents. HYTRANS covers the period from 2005 to 2050. The current version divides the United States into three geographic regions and three fuel density demand regions within each geographic region. Unlike NEMS and MARKAL, HyTrans does not attempt to model the entire energy system, but instead links to NEMS to obtain information on the interaction of the hydrogen economy with the larger economy and the environment.

A specific focus on the transition period – whose length will vary depending on how rapidly a hydrogen vehicle economy is adopted but might last two or three decades -- is necessary because this period will have characteristics that are quite different from those likely to be present in the longer term, when hydrogen has thoroughly penetrated the light-duty market. These differences include:

a. New vehicle, production, and distribution technologies may be considerably more expensive than they will be in the longer run, because they won't yet have had the benefit of years of learning and mass production. In addition, early vehicle models (and possibly early production equipment) may have unforeseen maintenance problems that will likely be eliminated or considerably reduced in the longer term.

b. Technology introduced during the transition period may become outmoded quite rapidly, because technology change will be swift during this period. This may cause problems for vehicle resale and create an incentive for potential purchasers of vehicles, small production facilities, and other technologies to delay their investment and let others take the risk of being early adopters.

c. The problems associated with limited availability of refueling facilities, shortages of trained mechanics, and difficulties with other parts of the vehicle and fuel infrastructure; performance and maintenance issues of early vehicle technology; higher costs; and the uniqueness of the vehicles means that, during the initial stages of the transition, the potential customer base is limited to fleets and to "early adopters," whose buying characteristics are likely to be quite different from the majority of the total population of potential purchasers.

d. Investment risks are much higher during this period, demanding higher risk-related rates of return, etc. In particular, during the transition the risk of stranded investments may be quite high, because infrastructure must be built in advance of hydrogen demand.

Because of these factors, substantial government involvement in promoting a transition appears to be essential to success, although the precise nature of such involvement requires extensive analysis.

This paper has two purposes:

1. To present insights about the process of evaluating a transition to hydrogen based on a literature review of papers and presentations describing scenarios of a future transition to extensive hydrogen use in the U.S. light-duty vehicle and stationary markets;.
2. To apply these insights towards suggesting ways to strengthen the EERE-sponsored models used to analyze a transition to hydrogen.

It is useful to point out that it is not possible at this time to identify a “best” approach to modeling a transition to hydrogen, even if the model users and their analytic requirements can be clearly defined. Methods for analyzing long-term energy market transitions are in their infancy. Also, a transition to hydrogen fuel cell vehicles will rely on novel technology with which consumers have no experience and whose costs and performance are highly uncertain. There is limited experience in analyzing futures under this level of uncertainty.

2. APPROACH

The approach of this study was as follows:

- <u>Literature review</u>: The literature on future scenarios of hydrogen use was reviewed, along with some additional material debating the pros and cons of future hydrogen development. The scenarios reviewed varied from Statewide to national, and a few foreign countries, of greatly varying magnitude. T**he primary focus of the literature review was on methodology rather than results, i.e. on the type of analyses conducted, the variables used to describe the scenario outcomes, the use of reference scenarios, the documentation provided, and other features that can inform the process of evaluating future hydrogen transitions -- not on the magnitude or geography of the hydrogen transition described. Unfortunately, there was a significant delay between completion of the literature review and the remainder of this study; as a result, literature published after August, 2005 is not covered in this report.**
- <u>Identify analytic issues</u>: A variety of analytic issues associated with evaluating a hydrogen transition were identified by examining and comparing the analytic frameworks of the reviewed literature and by identifying gaps in the scenario analyses. Also, the literature discussing the pros and cons of a hydrogen transition yielded insights about areas of scientific controversy and calculations that required special attention from the modelers.
- <u>Formulate a “wish list” of requirements for a hydrogen transition model</u>: Based on the analytic issues identified above, a list was formulated of requirements for an “ideal” hydrogen transition model, recognizing that the requirements might conflict with resource limitations as well as shortcomings in analysis

methodologies required to evaluate key variables. A more practical approach for examining a range of policy questions might be to develop a few models designed for subsets of the range of questions and audiences.

- Characterize existing EERE-sponsored hydrogen models and contrast to the "wish list": Using the characteristics identified in the wish list as a guide, a questionnaire was designed and distributed to the modelers responsible for the EERE models asking them to characterize their own models for contrast and comparison.
- Identify opportunities for future model development: Such identification should flow from contrasting the model characteristics to the "wish list," taking into account the specific purposes of the models.

3. LITERATURE REVIEW

All in all, 47 separate items were reviewed for the literature review.[*] Appendix A lists the papers and presentations reviewed, and Appendix B presents each of the individual reviews. In a number of cases, slide presentations describing scenario analyses were reviewed but more detailed documentation was not obtained. Similarly, several of the papers are brief and may not represent the most extensive documentation available, although such documentation could not be located. Given the limitations of the scenario documentation obtained, it is possible that some of the scenarios were constructed with more analytic foundation than was apparent from their descriptions and described in this paper.

The literature review was completed in April, 2005, and a considerable period of time passed before this report could be completed. During this period, a substantial volume of new literature describing hydrogen scenario analyses has been published, but unfortunately this recent literature is not reflected in this discussion.

Table 1 presents the review format used for the majority of the reviews completed for this effort.

Table 1. Hydrogen Scenarios Literature Review

1. **Full citation, including web site if applicable**
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**:
    b. **Dates and interval:**
    c. **Extent of focus on transition; possibly break out 2010-2030?**
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price**
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.**
3. **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?**
    a. **Scope: LDVs only, total transport, other sectors included**
    b. **Geographic scope: regional, national, international**

---

[*] As noted, the review "closed" in April, 2005, and more recent literature is not covered.

   c. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies**
   d. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability**
4. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices**
5. **Identification of key roadblocks**
6. **Interesting results/conclusions**
7. **Comments on overall credibility (judgment by reviewer)**

Although the focus of the literature reviews was on methodology and insights that would be useful for evaluating transition modeling, the results presented by the scenario reports are of interest.

Many of the conclusions and results reported in the literature reviewed are “self-evident” and could have been anticipated from a general understanding of hydrogen characteristics, production and distribution methods, and vehicle technologies. These results can be summarized as follows:

- Hydrogen in transportation still has several technological roadblocks that will have to be overcome before it will be viable, and there are no guarantees that these roadblocks will be overcome.
- At the beginning of the transition, neither the fuel cell vehicles nor the hydrogen fuels are likely to be cost-competitive with conventional gasoline or diesel vehicles, also, potential purchasers of hydrogen vehicles must deal with the risk that the transition will stall and their investments will become useless. This problem demands a strong government role in the transition.
- The transition to hydrogen will be a period of rapid technological change and economic changes from the rapid growth of hydrogen production and distribution infrastructure. These changes may cause a portion of the new physical assets (for example, small-scale hydrogen production equipment) to become obsolete quite rapidly.
- Hydrogen vehicles will be competing with a moving target – conventionally-fueled vehicles will improve also, especially given the stimulus of competing with hydrogen vehicles; and hydrogen’s effect in reducing gasoline demand could cause gasoline prices to drop. Also, other vehicle types, e.g. hybrids, will improve as well.
- Reducing vehicle loads (by reducing vehicle weight, improving tires and aerodynamics, and making accessories more efficient) will allow easier hydrogen storage and cheaper fuel cell drivetrains, by improving efficiency and reducing drivetrain power requirements.
- Because H_2 production feedstock prices and other key factors will vary substantially from region to region (and even within regions), the transition may look different across these areas and may require different strategies.

Aside from these “self-evident” results, the scenario reports examine a wide range of issues, yield numerous insights, and present some interesting disagreements about key issues.

Some of the results and conclusions are quite important and probably *not* “self-evident,” that is, they appear to be valuable additions to the state-of-knowledge (or at least the state-of-knowledge among those who are not experts in this area). We would include among this class the following conclusions:

- A hydrogen economy is almost certainly going to be a high energy economy, because hydrogen production and distribution are energy intensive.
- Although the investments needed for a transition to hydrogen may seem daunting, they are not necessarily massively higher than those investments needed to maintain the current petroleum-based system.
- Substantial penetration of hydrogen into the vehicle market may cause dramatic shifts in the petroleum refining market, with drops in gasoline prices and the likelihood of shifts in refinery technology and operations.
- Although a hydrogen transportation system’s ability to use renewable electricity has been promoted as a means to greatly reduce greenhouse gas emissions from transportation, using such electricity to back out fossil electricity (or to power electric vehicles) will be far more effective at reducing such emissions. For the foreseeable future (until there is excess availability of renewable electricity) generating hydrogen might be considered a poor use of renewable electricity.
- Also, although electrolysis has been promoted as an effective way to produce hydrogen, making use of off-peak (thus cheap) electricity, the costs are likely to be high. Restricting hydrogen production to off-peak hours causes the “per kilogram of hydrogen” capital cost to be very high; and the more effective use of capital, producing hydrogen around the clock, will likely be accompanied by high average electricity costs.

There are some areas where there are sharp disagreements among studies, particularly in the area of the preferred speed and character of a transition to hydrogen and the “best” hydrogen production alternatives. For example, there is sharp disagreement about whether the transition should be fast or slow – obviously a crucial issue. This disagreement may revolve around the tradeoff between the advantages of quickly constructing a very broad infrastructure, to allow hydrogen vehicles to go anywhere (thus maximizing their market attractiveness), and the potential for a rapid deployment to create large numbers of vehicles and refueling facilities that might appear outmoded as technology moves on. Other factors in this disagreement might be the effect of deployment speed on construction costs (for example, the potential to outrun the supply of skilled labor) and personnel training capability and effects on the level and extent of government subsidies required. It is not clear, however, whether factors such as labor availability were accounted for in the studies.

As discussed earlier, the primary purpose of the literature review was to surface analytic issues that would, in turn, yield insights about how models could best evaluate a hydrogen transition. The next section discusses the analytic insights gained from the review.

4. INSIGHTS GAINED FROM THE LITERATURE REVIEW

4.1 Overview

If the literature reviewed is a good representation of the total literature on hydrogen futures, an important conclusion of the review is that the analysis of hydrogen futures is at an early stage, and that considerable additional work will be needed to provide appropriate guidance to DOE, and the federal government in general, in fine-tuning the hydrogen R&D program and formulating a strategy to accelerate hydrogen into the light-duty vehicle fuel market. Although the transition to hydrogen is the development phase that likely will require the most help from government, **most of the scenarios reviewed do not explicitly examine this phase but instead focus their attention on the long-term hydrogen economy**.

In addition, **none of the scenarios examined "surprises," that is, oil disruptions, global climate change discontinuities, or other events that might significantly and rapidly alter society's and individuals' calculus of a hydrogen economy's costs and benefits**.

Also, **in most of the scenarios, the crucial variables that specify the degree of hydrogen penetration were exogeneously specified**; they were *not* derived from an analytic computation of factors that might affect the market entry of hydrogen fuel and vehicles, such as fuel prices, vehicle costs, etc. In other words, the key scenario results – such as the number of gasoline vehicles replaced by hydrogen vehicles, the reduction in gasoline and diesel use, and changes in GHG emissions. – arise because the scenario developers have specified either the hydrogen vehicle penetration into the new fleet or, in the extreme, the total penetration of hydrogen vehicles into the complete onroad fleet. In the former case, the analysts use a vehicle stock model to track the roll-in of the hydrogen vehicles into the total onroad fleet. In both cases, the results are most useful in answering the question, "How would a successful transition to hydrogen affect oil use, emissions of greenhouse gases, investment expenses, and other important variables?" In either case, however, **there is no analysis that shows *why* hydrogen-fueled vehicles are purchased (and why the necessary refueling infrastructure and hydrogen production investments are made), and thus there is little to be learned about what conditions and/or policies would actually lead to this result**.

Further, **most of the scenario analyses did not test their results for realism**. Such tests might involve comparing the implied construction rates for infrastructure investment to historical rates during times when conditions demanded rapid new investment; computing how long it would take for cash flow to become positive for key investors; or even just explicitly cataloging what the drivers of the scenario would have to be to achieve the postulated levels of hydrogen production and consumption. In much of the reviewed analyses, levels of hydrogen production and sales of fuel cell vehicles are presented without an explicit discussion of the methodology used to derive these levels; although it is recognized that careful analysis may have been undertaken to develop the scenarios, in most cases this analysis is not described or even mentioned.

Despite the early stage of current scenario development literature, the literature review illuminated a number of issues about a transition to hydrogen and about how this transition might be explored that are worth sharing.

4.2 Choosing a Reference Case

Virtually all of the scenario analyses directly compare a scenario with extensive penetration of hydrogen into the light-duty fleet with another scenario in which hydrogen does not penetrate. This Reference Case is used to compute reductions in greenhouse gas emissions and oil consumption, capital expenditures, and a host of other comparative values stemming from the hydrogen penetration. S**election of an appropriate Reference Case is thus crucial to the validity of the study results, because so many of the results are "differences" between the two cases rather than absolute values.**

Reference Cases may have several uses, but the most common use in the reviewed papers is to address the following question: What difference will introduction and penetration of hydrogen vehicles into the LDV fleet make to greenhouse gas emissions, oil use, and other important variables? For this question to be appropriately addressed, the hydrogen scenario should differ from the Reference Case only in policies designed to promote hydrogen use; otherwise, the hydrogen penetration should occur in the same "world" as the Reference Case. In other words, variables such as oil prices, consumer values, interest rates, and so forth should be the same *except to the extent that the hydrogen policies and their results may change them.*

Many of the scenario analyses chose reference cases from existing projections, e.g. the Energy Information Administration's Annual Energy Outlook (AEO) Reference Case, based on the National Energy Modeling System (NEMS). This type of reference case is appropriate, however, only if the hydrogen scenario(s) adopt the same input assumptions as the AEO, e.g. oil prices, economic growth rates, etc. and the basic policy prescription of the AEO, which is that no changes in energy policy are considered *except those policies that drive the penetration of hydrogen.* However, it must be recognized that the "world" described by such a hydrogen scenario would be a highly unusual one, where a series of heroic measures are taken to stimulate hydrogen's massive penetration into the light-duty vehicle fleet but where no other measures are taken to stimulate other technologies and behavioral changes that could help to accomplish the same ends sought with the hydrogen penetration. Also, the worlds described by the AEO Reference Cases used by the scenario analyses examined in the literature review (AEO2004 and earlier) are ones in which there are few reasons, aside from climate change, to seek a radical change in vehicle fuels, because the AEO worlds have plentiful supplies of liquid fuel obtainable at moderate prices. (However, more recent analyses using the latest version of AEO (2006) now have a High Oil Price Case that postulates a year 2030 oil price of approximately $90/barrel in 2004$. This scenario does represent a world where scarce and expensive oil supplies provide a strong incentive for a hydrogen transition. On the other hand, the AEO2006 Reference postulates a year 2030 oil price of about $50/barrel

– higher than in previous years but probably still representing a world with adequate supplies of oil.)

In reality, many consider that the Hydrogen Fuel Initiative is being undertaken to guard against a very different world from the one described in the AEO Reference Case – one in which oil has become scarce and expensive, and the potential for oil disruption is high enough to demand heroic measures to guard against U.S. overdependence on imports from unreliable sources. In other words, the Initiative is an insurance policy against the risk that the future will be considerably more perilous than foreseen by the AEO Reference Case. However, if this is the case, then a more appropriate Reference Case for analysis of hydrogen scenarios is one in which the condition of the world justifies taking heroic measures to reduce oil use (and possibly GHG emissions), although quite possibly without foresight. Although one possible Reference Case within this framework is the "No Policy Change" case, it should be recognized that the market would almost certainly react to this case by increasing LDV fuel economy to levels substantially higher than the AEO Reference Case values. The baseline vehicle for such a case might more appropriately be lighter and more streamlined than the AEO Reference vehicle, perhaps with a hybrid or diesel drivetrain and some penetration of alternative fuels. The net result of choosing such a baseline is that the net effects of the hydrogen economy will be less – perhaps considerably less -- than would be measured against a "business as usual" (BAU) scenario.

An added comment about the baseline drivetrain and fuel is that some of the policies used to drive the hydrogen economy may be general enough to affect a range of drivetrains and fuels. Policies might include taxes on gasoline; renewable fuels standards; fuel economy standards; and so forth. An integrated model will automatically capture the effects of these policies on competing fuels and drivetrains, but many of the scenarios are based on stock models or other simple models that require exogeneous assumptions about the competing fuels and drivetrains. It is the responsibility of the analyst to ensure that the effects of the policies on *all* alternatives are captured and used in scenario comparisons.

4.3 <u>Scenario Development Methods</u>

There are several methods of developing scenarios of hydrogen penetration into the LDV fleet, some involving formal models of varying complexity. Although the value of these methods to their potential users depends in large part on the basic quality of the analytic process and the data used, their value also depends critically on what questions the users want answered.

The scenario development options are:

1. **Projection Model.** Use of a projection model such as NEMS requires specification of initial conditions and formulation of a "state-of-the-world" scenario that defines a time series of variables such as future oil prices (which may be allowed to change depending on how the projection unfolds), economic growth rates, policies, and so forth. In this method, the rate of hydrogen

development would follow from vehicle choice models (and possibly investment models), which depend in turn on variables such as the prices of competing fuels, vehicle prices, etc. The initial costs of hydrogen vehicles might be defined in the initial scenario input to the model, with the model then projecting future cost reductions with learning and scale, as vehicle sales increase.

2. **Optimization Model.** This type of model might be a subset of projection models that assumes that market behavior will follow an optimized path, e.g. towards a least cost solution. Another version of this model might start with a desired outcome, e.g. a hydrogen production target or a future goal for penetration of large numbers of fuel cell vehicles, and find an optimum path for achieving that outcome. The optimum can be defined in purely economic terms, e.g. least cost, or can incorporate societal goals.
3. **Stock Model Approach.** This is a simple approach whereby the outlines of a hydrogen scenario, for example sales of FCVs over time, are specified and a stock model is used to translate sales into a time series of actual numbers of FCVs in operation. Generally, the initial hydrogen scenario represents either a project goal or an option developed by expert judgment. An alternative is to specify a target hydrogen penetration (total vehicle stock or hydrogen use) and use a stock model and trial-and-error to find a vehicle sales pathway that will reach that penetration. In this case, however, it must be recognized that there are multiple pathways that will reach the same penetration.
4. **Pure Judgmental Approach.** This is similar to the Stock Model Approach except that judgment is used to arrive at the "final product," the actual hydrogen scenario with on-road numbers of FCVs specified or the total hydrogen use in the LDV fleet for a future year. Approaches 3 and 4 are essentially equivalent since they both rely on expert judgment to project the outlines of a hydrogen development scenario; the 3rd approach asks for judgment about sales and the 4th asks for judgment about stock. Sometimes the judgmental scenario development is accomplished by a formal quantitative procedure. For example, with Battelle's Interactive Future Simulations method, expert judgment is used to identify a set of descriptors that are most important to the topic in question; alternative outcomes are defined for each descriptor; expert judgment is used to identify the probability of occurrence of the outcomes for each descriptor; expert judgment is again used to set up a cross-impact matrix whose components define how the occurrence of one descriptor affects the others; and a computer program is used to calculate the probabilities of occurrence of different sets of outcomes (scenarios). (Millett and Mahadevan, undated).

In general, this brief list of scenario analysis approaches moves from the most complex to the least (although it is quite possible that an expert-judgment-based approach using a cross-impact matrix may be more complex that use of a stock model coupled with a goal-defined level of hydrogen development). The potential benefit of complexity is the possibility of capturing subtle or counterintuitive outcomes arising from successful modeling of what is in reality a very complex process; the almost-certain cost of complexity is increased difficulty in understanding how the model works, and difficulty in deciphering the extent to which model outcomes may be driven by initial assumptions rather than robust analysis. One aspect of this increased difficulty is that, if one wishes to explore the impact of changing those variables one is most unsure of, the more complex models simply have more variables to examine, thus it is less likely that such exploration will be undertaken. One simple rule that flows from this tradeoff is the following: Do not value complexity in a model without understanding its details.

Another problem with complexity is that it demands an understanding of the processes being modeled that may or may not exist. For example, it would appear highly desirable to calculate the changing market share of hydrogen-fueled vehicles using a vehicle choice model dependent on various market variables (fuel prices, vehicle costs, vehicle performance characteristics, etc) rather than specifying the share exogeneously; the model with endogeneously-derived market share can then project how changes in market conditions (for example, a vehicle subsidy, or R&D success in reducing vehicle costs) will affect vehicle market share and hydrogen demand. On the other hand, a credible vehicle choice model demands a good understanding of how potential vehicle purchasers will actually react to a vehicle that may be quite different in many aspects from existing ones (thus, available revealed preference data on vehicle purchase behavior may not be fully helpful), in a time frame somewhat distant from today's. The choice, then, of whether or not to include a vehicle choice model is one of trading off the imperfect nature of the resulting model and the uncertainty it would add to the overall model results vs. the benefits it would provide in added model capability in evaluating alternative policies or the effects of different market conditions. This type of choice will be repeated many times in developing comprehensive hydrogen transition models.

As noted above, the variety of modeling or other approaches to scenario construction and analysis may be more or less suitable depending on the questions being addressed. For example:

Question 1. What are the costs and benefits of hydrogen development, including GHG emissions reductions, oil use reductions, investment costs, etc.? This question lies at the heart of government decisions about whether to pursue expensive R&D programs aimed at stimulating development of a hydrogen economy. The answers to this question will also influence decisions about whether to support a variety of policies designed to promote hydrogen use, although they may be insufficient to select the best among alternative policies aimed at the same outcome. Scenario analyses stemming from exogeneously specified levels of hydrogen vehicle penetration using expert judgment and stock models, or even expert judgment alone, may be satisfactory methods of addressing this question as it pertains to long-term costs and benefits. However, these methods will have difficulty evaluating the period of the transition to hydrogen. More sophisticated models may be capable of defining the timing and perhaps the character of a hydrogen transition more realistically than judgmental approaches.

Question 2. Will hydrogen development occur if the world unfolds as we think it will (e.g., if oil prices, economic development, policies, etc. occur as we expect them to)? Or, Under what circumstances will hydrogen development unfold? Theoretically, a projection model would be the best option (assuming it is credible), although judgmental approaches may well attempt to answer the question. To find out what various combinations of circumstances will yield hydrogen development, it would be necessary to rerun the projection model many times with varying inputs to identify those yielding a favorable outcome. An alternative way to address this question might be to use a stock model to project the results of a development scenario, and calculate the costs of the scenario under varying economic conditions to gauge the range of conditions for which it might be realistic. The problem here is that, given the large uncertainties in most of the key economic drivers and the very early stage of development of our ability to analyze long-term market transitions, these basic questions can at best be *addressed* – probably not "answered" -- by gaining insights from running the various models under a range of assumptions. Given this, it is not clear whether any type of model is "best" for addressing these questions.

Question 3. Given a desired outcome (e.g., x billion kilograms of hydrogen used in LDVs in the year Y, or more generally, satisfying transportation energy demand over a specified period at the least social cost), what is the most desirable path to get there? An Optimization Model is designed to identify a path to a specified goal that satisfies an objective function, e.g. "least cost," and thus can identify some aspects of the market path to achieve that goal. The alternative to using an optimization model is to examine a wide range of pathways using a simpler model and compare the results according to the same set of criteria used in the optimization model. Alternatively, an optimization model can be programmed to generate a number of alternative pathways within some incremental cost of the least cost pathway. The similarities and/or differences among these alternatives can provide insight regarding the flexibility available to achieve the goals cost-effectively. This approach can also identify alternatives that may be superior to the least-cost "optimum" with respect to characteristics not counted in the optimization analysis.

Question 4. What is an appropriate allocation of resources for an R&D Program for a Hydrogen Transition? What technologies most demand improvement? This question can best be answered by a model or analysis that can test the relative sensitivity of hydrogen transition outcomes (e.g. hydrogen vehicle penetration or total oil displacement) to different levels of success in R&D programs aimed at reducing the costs and improving the performance of key hydrogen production, delivery, fueling, and vehicle technology systems or improving other aspects of a transition. Theoretically, a simulation model that builds a hydrogen scenario based on market conditions and vehicle and fuel costs would most directly capture the effects of different levels of R&D success, by showing how R&D success will directly affect the rate of growth of hydrogen production and consumption. However, simpler models that rely on exogeneously-specified hydrogen scenarios will show the effects of different levels of R&D success on total investment and operating costs of the specified scenario, giving a strong indicator of the scenario's likelihood of becoming reality. Multiple runs with different scenarios can be used to obtain a picture of the effect of R&D success, though this appears to be a "second best" method.

Note that the added benefit of a simulation model that endogeneously constructs a scenario may be limited by gaps in understanding how investors will react to changed costs as well as other uncertainties (such as how FCV competitors – conventional gasoline and diesel vehicles – will adapt to increased competition, by improving performance and reducing costs).

4.4 Reality Testing of Scenarios

Some of the more complex models used to develop hydrogen transition scenarios create outcomes that are automatically tested for realism in some respects. For example, some models do not allow fuel production to expand faster than predetermined maximum rates; some models base vehicle sales on satisfaction of consumer preferences, that is, they use vehicle choice models; and some apply economic tests to investment decisions, that is, they demand satisfaction of minimum payback or other requirements. However, even the more complex models do not subject all important decisions to formal computation (for example, some key variables may simply be specified by the model user), and the majority of scenarios reviewed were developed without complex modeling or other processes that would guard against outcomes failing some important reality test. Given this lack of reality testing, it might be useful to develop a set of tests that could be applied to hydrogen transition scenarios to identify those with serious flaws.

Short and Greene have discussed[*] a variety of questions that DOE will need to answer in the process of helping to guide the analytic process of designing the Federal government's role in promoting the development of a hydrogen economy. Many of these questions relate directly to evaluating the realism of potential hydrogen transition scenarios, and these questions have helped in constructing the following list of issues that can be used either to formulate a realistic scenario or to evaluate the realism of a scenario after it has been developed:

1. **Investor behavior:**
    a. **For individual investor classes, do the required investments satisfy established investment hurdles?** Can we track the initial investments, operating costs, and revenues for individual actors (e.g., hydrogen producer, vehicle manufacturer, producer of refueling station gear, etc.) to explore the attractiveness of these businesses? For example, for an individual investor, can we determine how long it takes to get the project into the black and what the rate of return is?
    b. **If some of the investments that are implied by a scenario would not satisfy normal investment criteria, is it likely that larger investors (e.g. multinational oil companies) would recognize this and act to insure that the investments would be made anyway**, to allow overall program

---

[*] Short, W. and Greene, D., "Hydrogen Transition Modeling and Analysis: What are the Questions?," Powerpoint presentation to the H2A Analysis Working Group, July 11, 2003.

goals to be met? (For example, might large investors venture into temporary support of small-scale hydrogen production appliances to get the system started even though these appliances might be replaced before they can repay their initial investment?). ***Note: identifying unattractive individual investments will point the way to targeted government incentives to spur these investments without providing unnecessary incentives to those actors not requiring them.***

2. **Vehicle buyer behavior: Are buyer concerns about vehicle and service attributes accounted for in the scenario? Also, can we account for different types of vehicle buyers, e.g. early adopters?** Key buyer concerns may include:
    a. **Fuel availability**, including redundancy of distribution (e.g., are stations only on key highways and widely separated? If so, what happens if one goes out of service? Have the scenarios taken such factors into account?)
    b. **Vehicle price vs. vehicle attributes**, with "price" including fuel savings or added fuel costs. Has scenario development used vehicle choice models that account for such factors? If not, do the projected vehicle sales in the scenario seem to be reasonable based on the vehicle attributes and prices assumed in the scenario?
    c. **Likely availability of maintenance services**; Will potential vehicle purchasers be discouraged by initial lack of competition among service providers?
3. **Government policies/actions: Are government policies keyed to overcoming specific problems with investor and buyer requirements?** In other words, assuming problems are identified regarding shortcomings in vehicle attributes or failure of investment opportunities to satisfy investor requirements, are government policies designed to overcome these hurdles? (Of course, scenario development can be designed to be a 2-step process, with the purpose of the first step to identify areas where government policy changes are required, and the second step being the designing of appropriate policies).
4. **Infrastructure: Are the schedules for infrastructure development realistic?**
    a. Building hydrogen production plants, fueling stations, pipelines, vehicle production lines – accounting not only for normal plant schedules but also for system-wide limitations on construction workers, plant designers, etc.
    b. Schedules for training personnel for vehicle maintenance – Are they realistic?
    c. Timing of technology improvements/cost reductions – Do they mesh with our current understanding of technology "learning"?
5. **Relationship between the underpinnings of a hydrogen economy and the specified exogeneous variables**
    a. Do the scenario assumptions about oil prices, public attitudes about the environment, efficiency of the conventional ICE fleet, etc. (which generally are exogeneous variables, not determined within the model – assuming a model was used) make sense when coupled with development of a hydrogen economy? For example, if ultra-high-efficiency hydrogen vehicles are assumed in the scenario, they shouldn't be competing against low-efficiency conventional vehicles – because the conditions that cause

the hydrogen vehicles to be developed and sold would also cause conventional vehicles to become much more efficient.

   b. Does the scenario account for interactions between hydrogen development (and the large-scale resource use implied by hydrogen production) and resource prices – including a possible *drop* in oil prices as demand shifts to hydrogen. That is, does the scenario account for interactive effects among resources.

6. **Role of stationary hydrogen power and non-transport uses of hydrogen feedstocks in a transport scenario** – Does the scenario account for hydrogen development outside of the transportation sector that might affect hydrogen fuel prices, fuel availability, technology development, etc. For example, development of stationary hydrogen power may add hydrogen distribution infrastructure, and may allow hydrogen vehicles to "partner" with the facility by refueling there. Also, there may be sufficient overlap between development of the technology needed for stationary power and vehicle power (especially for hydrogen production) to yield synergistic gains, or simply to advance the state of technology which the vehicles and their infrastructure can then piggy-back onto.

   Non-transportation sources may also compete with transportation for hydrogen feedstocks, either for hydrogen production or other uses. Further, these same feedstocks may alternatively be used to produce other transportation fuels such as cellulosic ethanol or Fischer Tropsch diesel. **The effects here may be positive or negative depending on scale effects and resource limitations**. As noted in the brief discussion of ideal model characteristics, analysts must consider alternative uses for potential hydrogen feedstocks, especially because they may have stronger benefits in other uses.

4.5 Modeling the Behavior of Investors Facing an Uncertain Future

Analysts seeking to understand how investments are likely to unfold during a transition to hydrogen, or seeking to discover how investors will react to different policy options to create or accelerate such a transition will have to simulate the behavior of potential vehicle purchasers, vehicle manufacturers, and investors in fuel production and refueling infrastructure. The economic actors actually dealing with a real transition to hydrogen will face substantial uncertainty about future economic and resource conditions and may search for investment strategies that trade off some profit potential for lower risk. Under such conditions, many of these actors may seek investments that will do reasonably well under a wide range of future conditions rather than trying to find investments that will yield maximum profits under one "expected" future. This set of investments may be quite different from the set that would emerge from searching for investments that will maximize profits for one particular future. This overall analytic problem is made more severe because a hydrogen transition has been identified as a classic chicken-or-egg situation – the individual actors who will build different parts of the system don't know for sure whether the others will build their part, so they may fear getting stuck with stranded assets (a fuel supply and distribution infrastructure without enough vehicles to use it, or a vehicle manufacturing infrastructure – with many manufactured vehicles -- without sufficient fuel infrastructure to provide potential vehicle purchasers with the incentive to buy the vehicles). This intensifies investor uncertainty beyond what uncertainties in variables such as oil price would normally create.

The concern here is whether the available models can generate an understanding of likely investor behavior, to help develop policies suitable for an environment of high uncertainty. For example, optimization models search for a "best" solution (for example, a least cost solution) under specified conditions, sometimes under the assumption that investors are acting with perfect foresight of future conditions. This may provide a blueprint of a potential investment path to a least cost future (assuming the scenario is an accurate representation of the future), but it doesn't show how to get there in a free-market economy. Insight about investor options might be gained by examining alternative futures and finding investment paths that provide profits under a variety of conditions. For example, the MARKAL model can operate in a stochastic mode in which the user defines various states of the future, and the model will find the least-cost path for a distribution of these states. However, translating such findings into an accurate representation of likely investment behavior (or into selection of optimal policies for stimulating a transition) may be difficult.

Dealing with this problem demands that the modeler face some key issues:

1. There is universal agreement in the analytic community that the future course of oil prices and other variables affecting investor behavior is highly uncertain, but little agreement about the relative probabilities of different scenarios for these variables;
2. Further, there is little understanding about how *potential investors in a hydrogen economy* view the future;
3. Neither is there clear understanding of how such investors would behave even if we understood what their expectations for the future were. It is likely that there would be a wide range of behavior, even within defined groups such as vehicle manufacturers or fuel providers;

The implication here is that the choice of how much detail to put into the model – for example, (in modeling investment behavior) whether to treat the entire energy sector as a single actor, to disaggregate to the level of the individual firm, or to choose some other level of disaggregation – goes beyond the normal choice between simplicity and complexity (with simplicity offering lower cost, greater flexibility, and improved ability to understand how the model is behaving at the cost of less accuracy, and complexity costing more, reducing flexibility and making it more difficult to understand how the model is behaving but perhaps offer greater accuracy). Modelers also have to carefully consider just how far our state of knowledge will allow us to go in modeling investor behavior under conditions of great uncertainty. There is a real concern here that analysts do not know enough about investor behavior to truly utilize the potential benefits of greater model complexity and disaggregation.

4.6 A Boundary Issue, and an Actor Issue – How Important Is It to Track Individual Actors, Including International/Multinational Ones?

In the earlier discussions about reality testing of scenarios and the characteristics of an "ideal" transition model, the issue of disaggregating the investor community into individual actors was raised. Although most reviewed scenario analyses have focused exclusively on the environmental and energy security effects of the scenario (especially GHG reduction and oil displacement) and sometimes on the total investment cost, a few have tracked total cash flow for the purpose of identifying how long it would take for a hydrogen industry to start turning a profit. This is a form of reality test for the scenario, or at least a measure of how much subsidy might have to be provided by government. However, **these analyses essentially have treated the entire hydrogen industry, including vehicle manufacturers, hydrogen producers and distributors, and retail fuel sellers as a single entity**. This type of analysis can be quite useful if aimed at getting a general idea about the realism of the scenario and government's role, but it falls short of providing a means of testing government policies aimed at individual actors or selected groups of actors. On the other hand, it might prove quite adequate if it is likely that large corporate entities will form joint ventures in recognition of the enormous risks involved in establishing a hydrogen economy. In any case, the likely considerable value of disaggregating the analysis to examine something more detailed than the "single entity" actor should be carefully weighed against the analytical difficulties such disaggregation entails.

To carry this discussion a bit further, one of the scenario analyses examined in the literature review asserts that the automobile industry has its own "rules" for investing in new technology that are somewhat different than those rules observed by other industries. This provides some further impetus for strongly considering *at least* disaggregating investors into individual industry sectors.

Another potential benefit of tracking "actors" at a more disaggregated level is the possibility that learning effects can be more accurately gauged. Many scenario analyses model the effects of learning and mass production on technology performance and cost by establishing rates of decline of technology price dependent on the number of units produced, and similar relationships for technology performance. There are important questions in such analyses as to what the appropriate measures of production should be, given technology competition (and secrecy) among competing corporations and the likelihood that multinational corporations will be extremely important actors in a hydrogen economy. These questions intersect with questions about how learning occurs in multi-actor industries and within multinational corporations. In other words:

1. Is it reasonable to tie price decline rates to total U.S. production, or should more attention be paid to production by individual firms or coalitions.
2. Can production overseas by multinational corporations operating in the U.S. be ignored in such calculations?
3. Do we know enough about learning to justify worrying about such nuances?

4.7 Searching for "Swing" Assumptions

All modelers dealing with future hydrogen development probably would agree that assumptions will play a considerable role in driving the results of their analysis, because of the long time frames needed to develop a hydrogen economy, the early state of development of several crucial technologies (especially fuel cells and hydrogen storage systems), and uncertain consumer reaction to an automotive system with some characteristics that are sharply different from the current system. It probably is a truism that a search for those assumptions that combine the potential to strongly influence the model outcome and a likelihood that they may turn out to be unrealistic should be done for *all* models, so that users of the results understand their limitations and so that appropriate parametric analyses with alternative assumptions be produced. In the case of hydrogen transition modeling, this requirement is magnified.

In the paper by Tseng and Friley, [*] for example, gasoline prices are projected to drop in response to oversupply as total refinery throughput decreases. In response to the same trend, diesel and petrochemical feedstock prices are projected to increase. However, this outcome depends on the *assumption* that refiners will not be able to develop technologies that can cost-effectively change the output slate, or that refiners will not be willing to make the necessary investments in a time of increasing hydrogen penetration of the light-duty market. In the Tseng and Friley analysis, the decline in gasoline price causes the light-duty fleet to retain a substantial share of conventional drivetrains despite (assumed) hybrid drivetrains that are quite inexpensive…a good example of the cascading effects of an assumption that may be quite open to challenge. An alternative assumption, that refining technology adjustments *will* be available and that appropriate investments to modify refineries would be made, would significantly change the modeled outcome. The question of how modeling studies should deal with such "swing" assumptions clearly is deserving of significant attention.

5. A "WISH LIST" OF REQUIREMENTS FOR A HYDROGEN TRANSITION MODEL

The primary goal of this literature review and evaluation is to assist the review of a series of hydrogen transition models being sponsored by the Department of Energy and help to suggest improvements to these models. In advance of examining the models' characteristics, it should be useful to construct a template of an "ideal" model – that is, one constructed without resource constraints and without limits on model complexity -- of a hydrogen transition into the transportation fuels market. The characteristics of each of the DOE-sponsored models can then be compared to this template, *recognizing that it is unlikely and probably impractical for any individual model to attempt to satisfy all of the features of such an "ideal" model, and that this characterization should be dependent on the precise purpose of the model, that is, the type of questions the model is designed to answer. Further, as discussed above, model complexity may overwhelm the capacity of the modeler to provide adequate data and may hinder the exploration of alternative*

---

[*] Tseng, P., Lee, J., and Friley, P., "A Hydrogen Economy: Opportunities and Challenges," *Energy*, Volume 30, Issue 14, 1 November 2005, pp.2703-2720.

scenarios. It seems quite possible that the most practical approach to modeling a hydrogen transition will be the development of a few models that will each be focused on specific types or ranges of questions and audiences.

The “ideal” model might have the following characteristics (not by order of importance):

1. **Documentation.** Clear documentation, especially a strong description of the basic analysis methodology and identification of key embedded variables (what they are, and what their default values are); also, to the extent possible, provision of an honest evaluation of model sensitivity to starting assumptions, to help users properly evaluate the robustness of model output. Ideally, identification of “swing” assumptions – those which will have an especially strong effect on key model outputs – will guide the development of a standard list of assumptions that will accompany the model’s reporting of each set of scenario results.
2. **Output.** Ability to construct a variety of summary tables and multiple types of figures; ideal would be the provision of user ability to define/design the output tables and figures – to be able to specify time intervals and variables to be graphed or included in tables.
3. **Parametric analysis capability.** Flexibility to allow extensive parametric analysis – ease of changing exogeneous variables, with special focus on those variables a) to which the results are quite sensitive, and b) which are highly variable/controversial. Some examples:
    a. Assumed oil/gasoline prices
    b. Discount rates
    c. Investment hurdles for different investor classes
    d. Vehicle performance and cost measures (e.g., MPG, total vehicle cost), including Baseline vehicles
    e. Other vehicle attributes
    f. Construction schedules
    g. Learning rates for technology cost and performance
4. **Ability to do Monte Carlo simulations using probability distributions for key variables.** Given the issue discussed in 13 below, analysts may wish to have the capability to model hydrogen pathways over a distribution of future conditions (such as oil prices) rather than for just one set of conditions.*
5. **Reasonable level of spatial disaggregation.** Ability to distinguish between different geographic circumstances, e.g. rural, suburban, small and large city; and different types of resources. This clearly is crucial because the economics of hydrogen systems will vary substantially with factors such as the spatial density of vehicles and the type of feedstocks used to produce hydrogen.
6. **Ability to incorporate existing sources of hydrogen into the transitional hydrogen supply, including the expansion of existing operating plants and reopening of mothballed facilities.** It has become clear that the magnitude of existing hydrogen production in the U.S. is quite large, and there is a substantial production potential in currently non-operating plants, both of which should be

---

* To avoid unnecessary application of this capability, the sensitivity of key outputs to changes in (uncertain) variables can first be evaluated parametrically, with Monte Carlo capability added only when high sensitivity of outputs to the variables is demonstrated.

taken into account in a realistic transition scenario. Ideally, this capability would include a detailed representation of refinery processes, technology, and capital equipment in place; however, this might prove overly ambitious unless the transition model can be linked to an existing model of the industry.

7. **Robust vehicle choice model.** Embedded vehicle choice model with multiple buyer groups or use of a distribution of buyer preferences and characteristics and a full range of competing vehicle and fuel technologies, including advanced conventional vehicles, electric hybrids, etc. The first buyers of hydrogen vehicles (aside from government agencies and fleets) are likely to be "early adopters," who have markedly different characteristics than average vehicle buyers, and buyer characteristics will change over time as hydrogen vehicles grow in numbers, the hydrogen infrastructure expands, and vehicle prices change (with learning and mass production effects). A major roadblock here is limitations in the state-of-knowledge of vehicle purchase decisions.
8. **Scenario reality checks -- tracking.** Ability to track variables that can help measure scenario realism, e.g. cash flow for key investors, labor requirements for infrastructure construction (User should be able to specify these variables as output). This might require the model to be able to **disaggregate the cash flow of individual investment "actors."** The model should be able to address the question, "Would individual investors be willing to invest in this activity?," with regard to the multiple types of investments needed to construct a hydrogen system.
9. **Scenario reality checks – algorithms.** The model should contain algorithms that add to scenario realism either by automatically adjusting parameter values to avoid unrealistic values or by alerting the user when such values occur, e.g.
    a. Limits on the construction rates of large hydrogen production plants, the rate of buildup of the required labor force, etc. (alternative: user alerts when embedded maximum values are exceeded)
    b. Avoidance of treating dependent variables as if they were independent (or at least incorporating algorithms that check relationships among variables to avoid large anomalies). An example would be treating hydrogen use and gasoline price as if they were independent of each other, rather than considering that large-scale penetration of hydrogen into the transportation market could depress gasoline prices.
10. **Wide analytic boundaries.** Consideration of non-transport factors affecting hydrogen use in transport, e.g. hydrogen use in stationary power generation or residential energy services, or non-transport competition for hydrogen feedstocks. Also, the model should be capable of evaluating how hydrogen use in the transport sector can affect the rest of the energy sector and the economy as a whole, for example, by raising demand for hydrogen feedstocks and reducing demand for competing transportation fuels. In addition, in measuring GHG impacts, the model needs to properly attribute electricity used for electrolysis to the appropriate marginal power sources, *and compare the GHG effects to those that would occur from an alternative use of that power if it is renewable.* Some scenario analyses have used national average power generation or assumptions of a single power source as the "marginal" source, but the actual marginal source

may be quite different, and the validity of the GHG calculations depend critically on correctly identifying that source (or distribution of sources). A number of scenario analyses have concluded that the use of renewable electricity to generate hydrogen for fuel cell vehicles will save considerably less GHG emissions than using the electricity to back out fossil power, especially coal-fired generation. A final issue is geographic boundaries, since learning and mass production effects may apply across a wide geographic area, perhaps worldwide in some cases.

11. **Ability to model a variety of government policies.** This attribute is not really separate from the others, since government policies generally affect model variables such as costs (because of direct subsidies or R&D assistance), interest rates (because of loan guarantees), etc…..so the key to successful modeling is likely to be the ability to readily change variables (that is, attribute 3) or even basic relationships (attribute 12). However, highly aggregated models will have trouble modeling policies that are narrowly targeted to industry segments (e.g., very small scale hydrogen appliances) or geographic areas (e.g., rural areas). Models assuming perfect foresight may have trouble capturing the effects of government fuel price guarantees, though presumably the modelers will use proxies of the effect of reduced uncertainty, e.g. reduced hurdle rates, to simulate the effects of such guarantees.
12. **Modular structure.** The model should have a modular structure that allows submodels to be easily updated or replaced as new knowledge is gained about industry investment behavior, factors affecting technology cost, and so forth.
13. **Appropriate investment model, including investment rules and disaggregation of types of investors.** As discussed above, choosing an appropriate level of disaggregation for describing investors, selecting an appropriate investment model, and defining the rules for that model is made difficult by incomplete understanding of investment behavior under conditions of high uncertainty about future oil prices, significant technological uncertainty, and strong dependency of investment success on the investment behavior of other actors. Some models have chosen to use optimization algorithms programmed to maximize the Net Present Value of future investments and costs to achieve specified levels of hydrogen consumption. These models may start with an exogeneously-specified demand profile and search for least-cost solutions to meet that demand, perhaps assuming perfect foresight on the part of investors. Other models may take the same least-cost approach, but compute a hydrogen demand profile by integrating the supply and demand parts of the model. Rules other than optimization may also guide investment decisions. And instead of perfect foresight, decisions may be made on the basis of "myopic" foresight (investors base decisions on expectations that current prices will continue), or using probability distributions for future oil prices and other key variables. The level of disaggregation may range from treating the entire energy system as a single actor to evaluating the behavior of individual firms in separate vehicle manufacturing, fuel production, and fuel distribution sectors.

    We are not prepared to identify an "optimal" investment model for hydrogen transition models, because of the difficult tradeoffs discussed above. The best we can say here is that different investment models answer different questions, and it is extremely important that both modeler and client understand what question the model is actually addressing, the basic underlying assumptions of the model, and its limitations. As noted earlier, an optimization model identifying a least cost solution for a projected oil price path defines an optimal investment path (assuming the price forecast is correct), but doesn’t predict the path investors will actually take. Although it seems possible that multiple runs of such models, under different scenarios, may allow a more realistic picture of likely investor behavior to emerge, it is necessary that a methodology for doing so be explicitly defined. And simulation models, while actually projecting investor behavior, do so with the limitation that there may be incomplete understanding of the rules real-world firms will follow during a hydrogen transition. Further, as discussed above, there appears to be a dissonance between simple model characterizations of investors’ view of the future (e.g., perfect foresight, “myopia) and actual investor behavior, and this dissonance is not likely to be overcome by analysis procedures such as increasing hurdle rates when investor uncertainty is high.

6. RESULTS OF THE MODEL REVIEW

6.1 Introduction

A primary goal of this study is to use the insights gained from the literature review to help strengthen the Department of Energy's hydrogen transition modeling effort. To complete this effort, it was necessary to understand how each of the three models dealt with the issues raised in the review, to discover, for example, how the models treat the various actors who will influence the hydrogen transition, or how the models treat the process of technology learning. Because the available model documentation is extremely lengthy and complex, and the models are still being developed and thus are in transition, the most efficient way to gain the necessary understanding was to recruit the modelers themselves to provide the needed model descriptions. To assist in this process, a questionnaire based on the insights gained in the literature review was sent to the modeling teams developing and running the three hydrogen models. The questions focus on the key issues discussed in the previous sections, and aim to ferret out how each of the models deals with these issues. The modelers – primarily David Greene and Paul Leiby of Oak Ridge National Laboratory (HyTrans), Frances Wood of OnLocation, Inc. (NEMS-H2), and Chip Friley of Brookhaven National Laboratory (MARKAL/DOE) -- were extremely generous in contributing their time and expertise to answer our questions. Table 2 presents the combined results of the questionnaires (some of the answers have been edited for clarification or altered based on follow-up conversations with the modelers).

In interpreting the results of the questionnaires in the context of the insights gained by the literature review, it is important to recognize that model design involves a tradeoff among competing factors, including basic analytic goals, model complexity, and the ease of interpreting results and recognizing the limitations of particular analyses. Analytic goals may directly compete with each other. For example, integrating various parts of the energy sector (to learn how changes in one part of the sector affect other parts, e.g., how changes in energy efficiency affect energy prices) may limit the model's ability to evaluate specific future scenarios -- the relationships among the key variables may make it impossible to replicate a particular scenario in the model, although trial and error may make it possible to approximate a scenario. Further, a desire to model certain interactions may be stymied by limitations in our basic scientific understanding of the interactions rather than by a lack of pure modeling capability. Selecting how to trade off these competing values requires an intimate understanding of the subject matter, the state of the art of energy modeling, and the needs of the Department of Energy (or any client); this level of understanding goes beyond the scope of this analysis. Consequently, rather than making recommendations for specific actions, this discussion attempts only to point out, for consideration by the modelers and their sponsors, some potential areas where modeling changes might strengthen the models' ability to help understand a hydrogen transition. These areas are discussed below:

Table 2. Expanded Hydrogen Modeling Comparison

	Questions for Hydrogen Modelers	**NEMS-H2**	**HyTrans**	**MARKAL**
Purpose	State what the purpose(s) of the model is (are), stressing those that have shaped how the model is formulated.	NEMS was designed by EIA to project the energy, economic, and environmental impacts of alternative energy policies and of different assumptions about energy markets. NEMS-H2 builds on that model to analyze hydrogen futures under various conditions and policies, especially the impact of a hydrogen economy on the U.S. energy system.	HyTrans purpose is to represent the interactions of consumers (vehicle purchasers and users), fuel suppliers (from hydrogen producers to retailers) and vehicle manufacturers in the market, in order to create realistic scenarios of the transitions to hydrogen-powered light-duty vehicles, explore the roles of advanced technologies in transitions, analyze the impacts of policies on the transition and evaluate the economic costs and benefits of achieving a transition to hydrogen.	MARKAL was developed to analyze the role of technologies in energy system and environmental planning and policy analysis. The hydrogen portion of the model was developed as a part of the GPRA analysis-and has focused on technologies where U.S. DOE R&D efforts have been focused.
Time Horizon		Currently 2030, to be extended to 2050, annual increments	2000 to 2050 in 5-year increments	2000 to 2050 in 5-year increments
Geographic Differentiation		9 Census regions with 3 markets (different rural/urban classifications) defined within each.	3 geographic regions (West, Northeast, Rest of US) and 3 subregions within each (different densities of demand)	U.S. as a single region
Model Output(s)	- Which variables (dependent and independent) does the model output include, as a default (focus only on variables relevant to the	Hydrogen production by technology, market, and Census division, fuel cell vehicle sales and stock shares, fuel cell vehicle prices and efficiencies, hydrogen consumption, hydrogen prices by market and region, fuels consumed for hydrogen production and delivery, carbon dioxide	The model predicts the following key variables endogenously over the period 2005 to 2050: The market price of hydrogen by region; Hydrogen quantities produced by process, feedstock and	Model projects fuel cell vehicle market shares and hydrogen consumption, production of hydrogen by technology, cost of hydrogen and competing fuels, feedstock consumption for hydrogen production and related carbon emissions. The model will also track total energy system costs and the

	hydrogen transition)?	emissions associated with hydrogen production.	region; New LDV vehicle sales by technology and fuel type; The market prices of LDV by technology and fuel type; Vehicle stock and vehicle travel by technology and fuel type; The number of refueling outlets by region; The number of makes and models by technology and fuel type; Capital investment in production by process and region; Capital investment in delivery infrastructure by type and region; Gasoline displacement, GHG emissions, and various cost measures.	displacement of other fuels. At present, the U.S. is treated as a single region; use of census regions and urban/rural/suburban segmentation are being pursued.
	- Can the output be user-specified? If so, what additional variables can be added?	More detailed information is available for debugging purposes, such as components of hydrogen prices, hydrogen fuel availability	Yes. So far most of HyTrans development effort has been on model structure, not user interface. But an enormous range of tabular results and graphs are generated with post-processing commands.	MARKAL has standardized output tables that should cover most data related to hydrogen production, distribution and consumption. Most (if not all) of the output from model calculations are available in the output file.
	- For user-specification of output, how difficult is it to change output variables? Briefly describe what the user has to do.	Variables in model would need to be identified and added to intermediate output files (not easy for non-NEMS user).	For many variables there are switches in a text file that can be changed readily before executing a model run. Other variables can be created by editing the GAMS code.	It is relatively difficult to change the MARKAL output files. However, more information about technologies and the details of their penetration can be obtained by running scenarios with and without the technology (this applies to all the models

	Questions for Hydrogen Modelers	**NEMS-H2**	**HyTrans**	**MARKAL**
Parametric analysis capability	Describe how the model is set up to do parametric analysis. How easy is it to change the following variables (that is, do you have to rewrite code? Are there simple user prompts?):	NEMS-H2 does not have a GUI interface. Inputs are changed through relevant input files for the HMM or transportation model.	In general, changes to input data and parameters require either changes to a spreadsheet file or editing a text file.	MARKAL's data inputs can be changed relatively easily through the ANSWER interface. The EPA-RTP group has developed techniques to automate sensitivity analysis. We have taken preliminary steps to incorporate these techniques.
	- Assumed future oil and gasoline prices	Generally solved for endogenously within NEMS-H2. Relatively easy to run alternative world oil price cases. HMM and transportation can be run together without rest of model and delivered oil prices specified through input files, but it is not very easy for a non-NEMS modeler to do. If this were going to be a routine use, new input price streams could be established.	Each of the standard AEO oil price cases (High, Mid, Low) with associated oil, gasoline and other prices are selectable with a switch. Other paths may be entered.	Oil prices are determined endogenously, although the user can easily adjust prices by changing the supply curves or by applying a cost multiplier or additional cost adder to oil or gasoline prices.
	- Discount rates	Specified in an input file	A single parameter in the data file.	Discount rates can be changed for individual technologies
	- Vehicle performance and cost, including baseline vehicles	Conventional gasoline vehicle characteristics are endogenously derived. FC vehicle characteristics can be user specified as relative to the conventional vehicle (incremental cost and mpg multiplier).	Changes are made to a spreadsheet which produces an input table for HyTrans.	Vehicle capital and O&M costs and vehicle fuel efficiencies can be changed
	- Learning rates for technology cost and performance	Learning has not yet been incorporated for hydrogen production and FC vehicle technologies. but is planned for the next version.	Changes made to spreadsheet, which are then exported to HyTrans	MARKAL can only be run with technology learning for costs . The use of technology learning is a user choice and the user can adjust the learning

				rates.
	- Plant construction times	These are implied in the installed costs.	NA	Construction times are not an input in MARKAL. The user can model the capital cost reduction (due to reduced capitalized interest) exogenously and then adjust the MARKAL investment cost parameter.
	- Other variables (list)	Vehicle make and model availability can be user specified	Many.	
Monte Carlo capability	Is the model set up to do Monte Carlo analysis? If so, for which variables?	No.	No.	This can be done using the EPA-RTP group's techniques, for all input variables.
Existing sources/plants	Does the model's data base of hydrogen sources include existing sources/plants?	No. Existing hydrogen production for refinery use is included in NEMS-H2 but is not available for meeting non-refinery demands.	At present, only for region 9. We are in the process of adding these data for all regions.	No

	Questions for Hydrogen Modelers	NEMS-H2	HyTrans	MARKAL
Vehicle choice model	Is there an embedded vehicle choice model?	Yes. It has a multi-attribute nested logit model.	Yes, a nested multinomial logit model.	No formal vehicle choice model. New vehicles penetrate based on economic tradeoffs of vehicle cost, O&M cost, fuel consumption, etc. within the context of the energy system, tempered by limits on penetration rates.
	Does the model have one or multiple representations of buyers (e.g., early adopters, mainstream buyers)? If there are multiple buyer groups, describe what they are.	Vehicle buyers are treated as a distribution through the logit function.	Buyers are represented by a probability distribution of individual-specific utilities and a shared typical utility function. Early adopters are therefore in the tail of the distribution.	We do not currently model different buyer types. This could be done by breaking transportation demands into different categories and using separate hurdle rates for each group.
	Do the buyers take account of fuel availability and availability of vehicle maintenance services in their purchase decisions? If yes, briefly describe how.	Yes for fuel availability. Low fuel availability decreases consumer "utility" and therefore reduces market share for those vehicles. The function imposes a steep penalty for very low availability, but little penalty once availability reaches around 10%.	Yes. Fuel availability is an explicit variable in the representative consumer utility function. The value of fuel availability is derived from the value of time saved by not traveling as far to obtain fuel. Maintenance costs are included but not the availability of maintenance service.	No
Scenario Reality Testing	Does the model implicitly or explicitly take account of the following limitations on how the scenarios develop?			
	- Limits on plant	Not in current version.	Maximum expansion rates for production of each vehicle and	Limits on plant construction schedules would be implicit in the initial

	construction schedules;		fuel type are specifiable.	technology start date and growth bound parameters.
	- (If the model is not integrated with the rest of the economy,) the effects of growing vehicular hydrogen use on gasoline prices and hydrogen feedstock costs	Included since model is integrated.	There are feedstock and motor fuel supply curves derived from NEMS model runs. As demand for feedstocks increases, the price is bid up.	The model is integrated with the rest of the economy.
	- The need for the required investments to satisfy established investment hurdles (Describe how the hurdles are applied….to the hydrogen industry as a single entity, to individual actors or groups of actors?).	Investment hurdle rates are incorporated in determining hydrogen production and delivery costs. Production and delivery each treated as single entity. Hurdle rate on vehicle purchases (and implicitly manufacture) treated by vehicle choice coefficients.	Investment hurdle rates are implicit in the cost functions for hydrogen production and delivery processes. These functions have been derived as reduced form equations representing the H2A production and delivery models. Individual actors are (all) fuel suppliers; vehicle manufacturers; consumers. Although individual vehicle manufacturing plants and fuel production plants (with different sizes for the latter) are represented, the only differences that arise among them are due to market conditions, not to differences in the "actors."	Hurdle rates are applied for individual technologies and can be adjusted separately for each production and distribution technology. The energy sector is treated as a single actor.

	Questions for Hydrogen Modelers	**NEMS-H2**	**HyTrans**	**MARKAL**
Electrolysis GHG Emissions	In calculating the GHG impacts of producing hydrogen using electrolysis, how are the marginal electricity sources determined?	Endogenously within the electricity model of NEMS-H2	Marginal electricity impacts are embodied in GREET model coefficients used to calculate GHG impacts, which can be changed based on different assumptions about the marginal electricity mix.	GHG impacts are determined endogenously in the model, on a national basis (no regional breakdown). Marginal electricity selected based on 3 seasons and 2 daily time slices.
"Learning" effects on cost and performance	Does the model examine non-transport uses of hydrogen, and are these included in calculations of learning effects?	Non-transport uses are not included in the first version of NEMS-H2. Later versions may include stationary fuel cells. Refinery hydrogen demand is included, but the hydrogen is not available to the transport sector.	Not included in the current version.	U.S. model does not currently model non-transport use of hydrogen.
	Is the learning calculation based on total units built/sold, or sales by smaller entities than "the industry" (treated as if it were a single entity?)? Explain.	Not yet incorporated. Likely to be done based on total units.	At present, HyTrans includes learning (and unlearning) for vehicle production. The current version treats drivetrains as the learning unit, with industry-wide learning. The next generation now under development treats components (batteries, on-board hydrogen storage, fuel cell stacks, motors and controllers, etc.) as the learning units. Learning in H2 production and delivery will be included in the next generation.	Learning would be calculated based on total units
	Are international sales (or production) included in equations of learning effects, or only U.S. sales	Not yet incorporated. Likely to be done based on US sales, although international sales could be considered.	International sales of vehicles will be included in the learning effects in the next generation.	The U.S. model would only be able to endogenously model learning for U.S. sales only. Global MARKAL type models (i.e. SAGE or ETP) could model learning effects of total

	(or production)?			international sales
Modularity	Does the model have a modular structure? Explain.	Yes. NEM-H2 is modular. Each of the major demand, supply, and conversion sectors is represented by a model within NEMS (see NEMS documentation for more info). A new Hydrogen Market module has been added.	The model is modular in the following sense: generalized functions are defined for sets of processes and activities: vehicle types, hydrogen production/delivery pathways, feedstock and fuel supplies, and for regions and years (periods) in the model.	Yes and no. The model is not modular, however, the inputs for individual sectors or groups of technologies can be entered into separate input files and the model can be run with or without these input files..
	How easy is it to "swap out" submodules, to update the model?	Relatively easy as long as all variables communicating with rest of NEMS-H2 remain unchanged. It is easy to run only a subset of models and use a previously saved database for variables that usually are from models not being run.	Adding a new region, technology, fuel, H2 production or delivery pathway etc. within those sets is simply a matter of naming the new region/process/fuel and adding the needed parameters to tables.	Very easy

	Questions for Hydrogen Modelers	NEMS-H2	HyTrans	MARKAL
Objective function for optimization analysis	If the model incorporates optimization routines, describe the default optimization function.	NEMS-H2 overall is a simulation, rather than a global optimization model. The HMM uses an optimization routine, where the objective function is to minimize the cost of producing and delivering hydrogen to markets within regions.	The model optimizes societal welfare, as would a competitive market (i.e., the discounted sum of consumers' and producers' surplus), over the time horizon of the model. GAMS allows a variety of optimization routines (software) to be used.	Least cost optimization
	Is there flexibility in choice of the objective function? If yes, what are the other options?	The HMM objective function could be modified for future versions..	The objective can be varied from a private/market perspective to a societal perspective by the inclusion of "external" valuations of oil use or GHG emissions. The modelers are developing alternative objective functions that deviate from complete knowledge.	The objective function can be adjusted to include an environmental damage function. Also, the model has a "Modeling to Generate Alternatives" mode that generates a variety of solutions within a user-specified cost increment of the least cost that meet all other modeled constraints.
	Does the model allow the trading off of risks and rewards (profits, time to payback, etc.)? Explain.	For hydrogen production and delivery these are implicitly included through the framework for calculating annualized capital recovery requirements. For vehicle purchases, trade-offs are implicitly included through the consumer preference coefficients related to vehicle cost and cost of driving.	Yes. Profits in different future time periods are traded-off according to a user-specified discount rate.	This would be done by adjusting the technology specific hurdle rates
	Does the model assume perfect foresight on the part of investors? If not, explain how their uncertainty about	The Hydrogen Supply Module assumes perfect foresight, though some other NEMS demand modules assume myopic foresight whereby decisions are made based on current	The current version assumes perfect foresight. The next generation will also allow limited foresight over a specified time horizon.	MARKAL can be run with perfect foresight or myopically. There is also a stochastic version of the model

	future outcomes is dealt with.	conditions. The NEMS electricity module also uses perfect foresight.		
One actor or multiple actors?	Does the model deal with a single "industry" or multiple actors?	Each sector (e.g. hydrogen production, vehicle purchaser, etc.) is treated as an actor.	As described above, the model represents endogenously all the key private actors in the market. Government actions are represented by policies specified by the user (e.g., taxes, subsidies, regulatory standards, etc.) Within the automotive and H2 production sectors individual plants are represented, and there are H2 production plants of different sizes; as noted, however, all vehicle manufacturing plants or all fuel production facilities will respond identically to market conditions.	MARKAL optimizes over the entire energy system.

	Questions for Hydrogen Modelers	NEMS-H2	HyTrans	MARKAL
Incorporation of other alternatives to gasoline besides hydrogen, e.g. cellulosic ethanol	Does the model have hydrogen competing against other alternatives to gasoline?	The transportation model include other LDV types: diesel, gasoline-electric hybrids, diesel-electric hybrids, dedicated electric, ethanol flex, ethanol dedicated, methanol flex, methanol dedicated, CNG, CNG Bi-fuel, LPG, LPG Bi-fuel fuel cell gasoline	Yes. There are a variety of alternative vehicle technologies, including gasoline and diesel ICEs, gasoline and diesel hybrid vehicles and hydrogen ICE vehicles. Technologies for other alternative fuels and vehicles (ethanol, CNG, LPG) are currently de-activated, allowing a greater focus on hydrogen.	MARKAL currently models conventional and hybrid gasoline vehicles, advanced diesel and hybrid diesel vehicles, plug in hybrids, as well as CNG and electric vehicles. Ethanol blends in gasoline can currently be adjusted up to 85%.
	Explain how they are examined, if in a different manner than hydrogen is.	Only hydrogen vehicles are segmented for 3 markets within each Census Division.	All are treated in the same manner: each fuel must be supplied, offered at some fraction of retail sites, and compatible vehicles must be produced according to similar learning, scale and model diversity considerations.	These are examined in the same way.
Policies	Which specific policies can be examined by the model? Please list them.	Various types of hydrogen technology tax incentives and subsidies; fuel price taxes, carbon emission taxes or caps, improved technology through R&D	Vehicle taxes and subsidies. Fuel taxes and subsidies. Investment subsidies (production or retail). Fuel economy standards (including CAFE credits for special vehicle technologies). Alternative fuel or vehicle sales mandates. Carbon taxes or carbon emissions standards.	Tax incentives (both consumer and producer), rebates amd feebates. environmental restrictions (CO2) and R&D induced technology improvements. EPA's version can model restrictions on criteria pollutant emissions.
	Which policies can be examined only indirectly, please explain.		R&D policies/investments are modeled via impacts on the rate and extent of technological progress (which is explicitly	Policies not stated above may only be examined indirectly.

			represented). Education and public information. Codes and standards (through vehicle and fuel costs).	

Citations and websites that document the working of the models

Documentation for the MARKAL Family of Models, October 2004.
http://www.etsap.org/documentation.asp
http://www.etsap.org/Tools.asp

Additional information on the U.S. MARKAL model can be found from the EERE GPRA documentation reports (http://www1.eere.energy.gov/ba/pba/gpra.html)

Conceptual Design for Representing Hydrogen in NEMS, December 2004
Documentation of Beta 1.0 version of NEMS-H2, March 2006.

6.2 Parametric Analysis

For all three models, conducting parametric analyses requires manually rerunning the models, with each new model run containing changes in the values being evaluated. This will not stop parametric analyses from being conducted, but will make these analyses a bit more difficult to conduct and might discourage a full array of them from being undertaken. This is potentially an important issue because many of the key variables in hydrogen transition analysis are highly uncertain and because evaluating potential policies for assisting the transition will require the systematic evaluation of several levels of application to find "best" solutions. EPA is using a free, publicly available modeling framework for doing parametric sensitivity analysis[*] with MARKAL; this framework may be applicable to the other models.

6.3 Monte Carlo Capability

In a model, a Monte Carlo capability signifies the model's ability to substitute a probability distribution for a single-value parameter and conduct random sampling of the distribution to construct a solution in the form of another probability distribution. In other words, the modeler may substitute a probability distribution of possible world oil prices for a single price value and then run the model multiple times sampling the distribution randomly, each time generating a different solution depending on the particular oil price associated with that solution. One output of the model, e.g. hydrogen production for transportation in the year 2045, will vary depending on oil price, so the complete set of solutions will yield a probability distribution of hydrogen production. As with parametric analysis capability, discussed above, the high level of uncertainty of key parameters driving a transition to hydrogen places a high value on the ability to deal with this uncertainty, and Monte Carlo capability will be valuable where there is some understanding of how likely different parameter values might be. Currently, among the three models, only MARKAL has incorporated Monte Carlo capability – not as part of the model, but in operating the model as part of EPA's Multimedia Integrated Modeling System (MIMS).

6.4 "Learning" as a Driver of Cost Reduction and Performance Enhancement

It is widely recognized that a transition to hydrogen will involve massive changes in vehicles and infrastructure, beginning with many costly technologies that will experience cost reductions and improved performance over time. The cost reductions and improved performance will result from gradual improvements associated with experience gained from increasing production of the new technologies, with redesigns both of the technologies and their means of manufacture. NEMS-H2 as of yet does not attempt to model learning. HyTrans and MARKAL do model learning, although the learning effects in MARKAL are confined to cost reduction.[†] In HyTrans, learning proceeds according to the number of drivetrains produced; the next version will track learning according to

---

[*] Personal communication, Dan Loughlin, USEPA.

[†] Learning effects can, of course, be simulated outside the model by changing input variables -- increasing efficiency and reducing cost over time. This could allow, for example, an examination of the relative importance of learning compared to other factors in determining commercial success of alternative technologies. However, the value of simulating learning effects this way is limited, because this will not allow the model to award learning benefits selectively, i.e. only to technologies that are penetrating the market as a scenario evolves and proportionately according to their production rate.

the number of individual components produced, which will allow learning effects to be captured across different types of drivetrains that may use some of the same components, e.g. advanced batteries or electric motors. MARKAL tracks learning according to the total units sold, which appears to be similar or identical to the current HyTrans approach. Both MARKAL and HyTrans track drivetrains or units on an industry-wide basis in the United States, which implicitly assumes that learning is fungible across companies and ignores learning effects that may occur on a worldwide basis by multinational corporations. Although this approach might be challenged, other approaches such as tracking by company might be difficult (because design and manufacturing of components may be handled either by vehicle manufacturers or by suppliers serving multiple manufacturers) and because our understanding of learning effects is still evolving. Nevertheless, learning is a crucial driver of the cost reductions and performance improvements that must occur for a hydrogen transition to succeed, and it would be worthwhile for the modelers to focus attention on improving the models' handling of learning effects.

6.5 Contribution of Existing H_2 Sources

Current production of hydrogen in the U.S. economy is quite large, with primary usage for upgrading oil feedstocks in petroleum refineries and for producing fertilizer. Current high natural gas prices have caused substantial fertilizer capacity to be shut in, and there is excess hydrogen capacity. Some analysts have projected that current hydrogen capacity may play an important role in a transition to hydrogen use in the transportation sector, though such a role will depend on the future of domestic fertilizer manufacturing and future trends in petroleum refining, and remains somewhat uncertain. Only the HyTrans model accounts for any current hydrogen production capability in examining a future transition, and this capability currently is restricted to Region 9 (but will likely be expanded).

6.6 Stationary Source Fuel Cell/Hydrogen Use

As noted earlier, non-transport use of fuel cells and hydrogen may allow some development of hydrogen delivery infrastructure or directly provide a refueling source for vehicles connected to the facility. Non-transport use may also promote some learning benefits applicable to transport use, e.g. in fuel handling and safety. At present, none of the three models incorporate non-transport hydrogen use. This appears to be an area that deserves further study.

6.7 Competition for Hydrogen Feedstocks

Hydrogen production will use feedstocks – natural gas, coal, biomass – that will have demand from other sources, some for competing transportation fuels and some for non-transport energy uses or for chemicals or fertilizer. MARKAL and NEMS include the entire energy system and can track feedstock use for all energy sectors, but may not track feedstock demand from non-energy sources. HyTrans can track feedstock use for competing transportation fuels, but cannot track other uses. This capability or lack of it may be important for biomass, if biomass becomes a cornerstone of a hydrogen transition strategy for greenhouse gas reasons. It will also be important for hydrogen production from natural gas, which is used primarily in the non-transport sectors and has encountered supply issues.

6.8 Investment Hurdles and Disaggregation of Investors

All three of the models apply profitability tests to potential investments, with only those investments that satisfy the tests becoming part of the transition scenarios developed. In reality, a variety of private and public entities may make such investments and will apply appropriate tests to their investment decisions, e.g. federal agencies, individuals (for vehicle purchase decisions), large multinational corporations (for major fuel production facilities construction), and so forth. None of the three models examines such investments at the level of all types of investors, but the degree of disaggregation varies substantially among the three. NEMS treats all hydrogen fuel producers as a single entity, with all companies involved in fuel delivery as another, separate entity. MARKAL generally treats the entire energy sector as if it were the sole investor. HyTrans does examine fuel producers and vehicle manufacturers at the individual plant level, although the representations of such plants are generic – each would respond identically to the same market conditions. The key concern here is whether the models can accurately portray investment decisions by different segments of the industry with such a high level of aggregation, and whether further disaggregation of existing models is warranted.

6.9 Analysis of Electrolytic Hydrogen Production

Although electrolysis is projected to be an expensive means to produce hydrogen, high natural gas costs and regional differences suggest that electrolysis could play an important role in some areas. The impacts of electrolytic production very much depend on which source of electricity is used – that is, given this production, which electricity source increases at the margin (that is, the generator used to actually produce the hydrogen may not be the marginal source). Identifying the true marginal source requires a detailed, disaggregated generation model. NEMS uses such a model, disaggregated to the level of individual regions. MARKAL uses a generation model, but it is a national model, and its temporal disaggregation is only to the level of three seasons and 2 time slices per day.[*] HyTrans uses emission and energy outputs from the GREET model, which allows only for selection of fixed generation mixes such as “national” or “California.” If electrolysis is considered an important hydrogen production mechanism, capturing its impacts may require a more sophisticated approach to identifying its electricity sources than used by MARKAL and HyTrans. Further, depending on the share of electrolytic hydrogen in the unfolding hydrogen economy and how long (and to what penetration into the transport sector) the model is meant to track hydrogen development, the investment model may be required to account for powerplant construction.

---

[*] A new version of the MARKAL source code has been developed, and is currently undergoing testing, that allows the user to specify as many seasons and time slices as necessary.

6.10 Investment Model

All three transition models develop scenarios of a hydrogen transition according to rules dictated by an objective function coupled with constraints (e.g. on technology growth or pollutant emissions). HyTrans and MARKAL search for an optimal solution, generally a least cost solution, for the combined investments encompassing all hydrogen development, whereas NEMS-H2 searches for a least-cost solution only for hydrogen production and distribution, with the behavior of other actors (consumers, vehicle manufacturers) simulated by investment rules without formal optimization. As noted, the level of disaggregation of investors varies markedly among the models, from MARKAL's "one actor" model (treating the energy sector as a single actor[*]) to NEMS-H2 disaggregating industry only into fuel production entity and a vehicle manufacturing entity, to HyTrans disaggregating both segments down to the individual plant level (though with identical behavioral characteristics for each plant).

Without judging the validity of each model's representation of investment behavior, the investment models and different levels of disaggregation do raise some important issues about the models' capability to evaluate a wide range of policies. For example, only HyTrans would appear capable of evaluating tax credits, subsidies, or other inducements applied to a limited portion of potential investors, although NEMS-H2 could evaluate broad subsidies or credits aimed at all fuel suppliers or all vehicle manufacturers. This is a particular concern because narrowly-targeted incentives may be valuable tool for stimulating a transition to hydrogen. For example, very small hydrogen production appliances might be needed early in a rollout of hydrogen, but might have a limited lifetime depending on how quickly overall hydrogen production and fuel cell vehicle sales ramped up (because hydrogen costs from such appliances might be considerably higher than those from larger-scale production facilities). Governments might want to focus higher incentives on such appliances because of this added risk. Models without disaggregation into individual plants (or groups of plants) at different production scales could not evaluate the effects of such policies.

6.11 Modeling Investor Decisionmaking Under Uncertainty

As discussed previously (section 4.5), most complex models – including the three examined here – attempt to evaluate investor behavior under assumptions of perfect foresight of future condtions such as oil prices, or in some cases with alternative assumptions (such as "myopic" foresight) that still assume that investors are behaving as if they "know the future." Presumably, uncertainty about the future can be expressed, in part, by demanding higher-than-normal rates of projected profits for potential investments in order to leave some room for disappointments in future market conditions. Further, running the model multiple times with parametric changes in projected conditions can demonstrate how projected investment behavior would change under changing (projected) market conditions.

What appears to be missing here, though, is a clear sense of whether running the models this way will likely capture the behavior of investors who know they face substantial

---

[*] This applies to the DOE and EPA versions of MARKAL. The version used by the Northeast States for Coordinated Air Use management (NESCAUM) represents electric utilities in considerable detail.

uncertainty in future market conditions and who may behave in ways that hedge their risks. Attempting to formulate an approach to dealing with this issue is well beyond the scope of this report….**but we urge the model developers to focus explicitly on the issue of appropriately modeling investor behavior given large actual and perceived uncertainties in future market conditions.**

7. CONCLUDING REMARKS

The review of scenario analyses, most of which were based either on simple stock models or done without formal modeling, emphasizes the value of the complex transition models currently being developed. These models force explicit decisions about a range of assumptions underlying the scenarios developed and ease the task of parametric analysis, which is crucial given the uncertainty associated with so many of the underlying assumptions.

The complexity of the models does place a responsibility on the model developers to carefully explain their model's strengths and weaknesses and to help users of the model or the model results understand the limitations of the results and how best to interpret them. Unfortunately, models are likely to appear to users as "black boxes" to which questions are addressed and answers are produced without the means to understand the process that translated one into the other. The modelers can automate some of this "explaining" process by designing model output to automatically include crucial input assumptions, but this is not enough. Model developers might want to include a thoughtful "warning to users" sheet (or short pamphlet) that alerts potential users to the pitfalls they should avoid in using and interpreting model results. However, it will be difficult to predict some of the problems that may occur in designing and interpreting runs, so modelers need to play an active role as advisers to users in designing and reviewing model runs, and they should make themselves available to serve as reviewers of interpretive discussions of results. Model users, in turn, should recognize the value of involving the model developers in an ongoing advisory role at all stages of an analysis.

There are strong differences among the three models examined here, and among these and other transition models currently under development. It is inevitable that there will also be strong differences among the *results* obtained from these models even where the questions asked and basic input assumptions are the same. Previous studies by the Energy Modeling Forum (at Stanford University) and others have proven very useful in providing comparative analyses of complex models, and it seems likely that duplicating such efforts with hydrogen transition models would prove equally useful.

APPENDIX A
LITERATURE REVIEWS FOR HYDROGEN TRANSITION SCENARIOS – LIST OF PAPERS/REPORTS/PRESENTATIONS

1. **U.S. DOE**: *Hydrogen Posture Plan: An Integrated Research, Development, and Demonstration Plan*, February 2004.

2. **Worldwatch**: Dunn, S., "Hydrogen Futures: Toward a Sustainable Energy System," Worldwatch Paper 157, August 2001.

3. **Sustainable Mobility Project**: Sustainable Mobility Project, *Mobility 2030: Meeting the Challenges to Sustainability,* 2004.

4. **U.S. EPA**: Laitner, J.A., et al, "Adapting for Uncertainty: A Scenario Analysis of U.S. Technology Energy Futures," *Energy, Environment, and Economics in a New Era: Proceedings of the 24th Annual North American Conference of the USAEE/IAEE*, Washington, DC, July 8-10, 2004.

5. **Oak Ridge National Laboratory**: Southworth, F, Pillai, R.S., and Greene, D.L., "A Hydrogen Transition Planning Model: Creating a Framework for H_2 Investment Analysis and Decision-Making," Oak Ridge National Laboratory, January 21, 2004 Draft.

6. **University of California**: Lipman, T., et al, *An Integrated Hydrogen Vision for California*, White Paper/Guidance Document, July 9, 2004.

7. **Joan Ogden**
    a. Ogden, J. and Kaijuka, E., "New Methods for Modeling Regional Hydrogen Infrastructure Development," Presentation to National Hydrogen Association Meeting, Washington, D.C., March 5, 2003.
    b. Ogden, J., Research at UCDavis on Design and Analysis of Hydrogen Distribution Infrastructure, presented to Fuel Pathways Technical Team, Oct 14, 2004
    c. Yang, C., "Integrated Infrastructure Transition Modeling for a Hydrogen Economy," Hydrogen Systems Modeling Workshop, Sept 20, 2004
    d. Ogden, J., "Hydrogen Systems Modeling: a) Transition Modeling: Early Results; b) Observations and Research Questions; Thoughts on the State of the Art," presented at the Hydrogen Pathways; Hydrogen Systems Modeling Workshop, UCDavis, Sept 20-12, 2004. **Reviewed**
    e. Ogden, J., et al, *Technical and Economic Assessment of Transition Strategies Toward Widespread Use of Hydrogen as an Energy Carrier. Draft Phase I Final Report, May 2004-January 2005*, January 31, 2005.

8. Farrell, A.E., Keith, D.W., and Corbett, J.J., "A Strategy for Introducing Hydrogen into Transportation," *Energy Policy*, 2002.

9. **CERA**: CERA, "The Hydrogen Economy: How Far and How Fast?," Private Report, 2003.

10. Bossel, U. and Eliasson, B., *Energy and the Hydrogen Economy*, January 8, 2003 (also, Bossel, U., Eliasson, B., and Taylor, G., "The Future of the Hydrogen Economy: Bright or Bleak?," October 28, 2004, http://www.oilcrash.com/articles/h2_eco.htm)

11. **NSCA**: Eyre, N., Fergusson, M., and Mills, R., *Fueling Road Transport: Implications for Energy Policy*, Energy Saving Trust, Institute for European Environmental Policy, and National Society for Clean Air and Environmental Protection, November 2002.

12. **National Research Council**: Committee on Alternatives and Strategies for Future Hydrogen Production and Use, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Academies Press, Washington DC, 2004.

13. **Amory Lovins**:

    a. Lovins, A.B. and Williams, B.D., "A Strategy for the Hydrogen Transition," 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, Virginia, April 7-9, 1999.

    b. Lovins, A.B., et al, *Winning the Oil Endgame: Innovation for Profits, Jobs, and Security*, Rocky Mountain Institute, 2004.

    c. Lovins, A.B., "Twenty Hydrogen Myths," Rocky Mountain Institute White Paper, www.rmi.org.

14. Wilson, J.R., "The Truth About Hydrogen (A Response to Amory Lovins' 'Twenty Hydrogen Myths'), Version 4.0," September 25, 2003, www.tmgtech.com.

15. **Lester Brown**: Brown, L.R., "Building the Solar/Hydrogen Economy," Chapter 5 in *Eco-Economy: Building an Economy for the Earth*, W.W. Norton & Co., NY, 2001. ***This is basically a treatise on wind energy, with hydrogen almost an afterthought…and its treatment of hydrogen is extremely naïve. Not useful.***

16. **Institute for Local Self-Reliance**: Morris, D., "A Better Way to Get From Here to There: A Commentary on the Hydrogen Economy and a Proposal for an Alternative Strategy," ILSR, December, 2003. ***This is a dissertation on using***

plug-in hybrids and ethanol from corn and cellulose to reduce oil use and greenhouse gases, as an alternative to hydrogen.

17. Berry, G., et al, "Hydrogen System Modeling: (1) Facts, Issues, Questions, (2) A Modeling Plan," Powerpoint Presentation, undated.

18. Sperling, D. and Cannon, J., eds, *The Hydrogen Energy Transition: Moving toward the Post Petroleum Age in Transportation*, Elsevier Academic Press, 2004:
    a. Chapter 12, "Lessons Learned from 15 Years of Alternative Fuels Experience – 1988 to 2003," McNutt, B. and Rodgers, D.
    b. Chapter 14, "Understanding the Transition to New Fuels and Vehicles: Lessons Learned from Analysis and Experience of Alternative Fuels and Hybrid Vehicles," Leiby, P. and Rubin, J.

19. **Science Magazine: "**Toward A Hydrogen Economy," *Science*, Vol 305, August 13, 2004.
    a. News: The Hydrogen Backlash
    b. Turner, J.A., "Sustainable Hydrogen Production"

20. **Tyndall Centre for Climate Change Research**:
    a. Watson, J., et al, *UK Hydrogen Futures to 2050*, Tyndall Centre Working Paper 46, February 2004.
    b. Dutton, G., et al, *The Hydrogen Energy Economy: Its Long-Term Role in Greenhouse Gas Reduction*, Tyndall Centre Technical Report 18, January 2005, United Kingdom

21. **ACIL Tasman**: "The National Hydrogen Study," Presentation to the Australian Institute of Energy Symposium, November 12 2003.

22. **Hynet**:
    a. Braess, H. and Bunger, U., "On the Way Towards a European Hydrogen Roadmap," Hydrogen and Fuel Cell Technology Platform – Launch Conference, Jan 21, 2004, Brussels.
    b. *Towards a European Hydrogen Energy Roadmap*, HyNet, May 12, 2004.

23. IIASA: Barreto, L, Makihira, A., and Riahi, K, "The Hydrogen Economy in the 21st Century: A Sustainable Development Scenario," excerpt of a paper submitted to the International Journal of Hydrogen Energy, March 2002.***applicable to a "affluent, low-population growth, equitable and sustainability-oriented B1-H2 world" – not especially relevant to this study***

24. **TIAX**: Lasher, S., Unnasch, S., and Chan, M., "Hydrogen Infrastructure: Energy, Costs, and Transition," Powerpoint presentation to 2004 Fuel Cell Seminar, San Antonio, TX, Nov 1-5, 2004. Also, Unnasch, S., "Hydrogen Transition Model

H2NowNPV," Hydrogen Systems Modeling Workshop, UCDavis, September 20, 2004 (Powerpoint presentation). Also, Lasher, S., "Fuel Choice for FCVs: Hydrogen Infrastructure Costs," DOE Merit Review, May 25, 2005, powerpoint presentation.

25. Berry, G.D., Smith, J.R., and Schock, R.N., "A Smooth Transition to Hydrogen Transportation Fuel," DOE Hydrogen Program Review, Coral Gables, Florida, April 19-21, 1995, Lawrence Livermore National Laboratory.

26. **Battelle:**
    a. Millett, S. and Mahadevan, K., "Commercialization Scenarios of Polymer Electrolyte Membrane Fuel Cell Applications for Stationary Power Generation in the United States by the Year 2015, Battelle Memorial Institute;
    b. Millett, S. and Mahadevan, K., "PEM Fuel Cell Scenarios to 2015, Powerpoint presentation, November 3, 2004.
    c. Millett, S.M., and Mahadevan, K., "Interim Findings on Scenarios of PEM Fuel Cell Applications for Stationary Power Generation and Commercialization in the United States by the Year 2015," Battelle Columbus, September 2004.

27. Thomas, C.E., Hydrogen Transportation Transition Pathways," Hydrogen Systems Modeling Workshop; Hydrogen Pathways Program, UCDavis, Sept 20, 2004, Powerpoint Presentation

28. Thomas, C.E., James, B.D., and Lomax, F.D. Jr, "Market Penetration Scenarios for Fuel Cell Vehicles," *Int. J. Hydrogen Energy*, Vol. 23, No. 10, pp. 949-966, 1998.

29. **Ricardo**: Owen, N. and Gordon, R., *"Carbon to Hydrogen Roadmaps for Passenger Cars: A Study for the Department for Transport and the Department of Trade and Industry*, Ricardo Consulting Engineers Ltd., RCEF.0124.31.9901, Client Confidential.

30. RAND: Silberglitt, R. and A. Hove, RAND Corporation, Scenario Analysis

31. **Tellus:**
    a. Bernow, S., "Challenges in Researching the Transition to a Hydrogen Economy," Nov 14, 2002
    b. Bailie, A., et al, *Hydrogen Transitions in a Greenhouse Gas Constrained World. Volume I: Main Summary Report*, Tellus Institute, August 2005, Draft.

32. Andrews, C.J., and Weiner, S.A., "Visions of a Hydrogen Future," *IEEE Power & Energy Magazine*, March/April 2004.

33. Tseng, P., Lee, J., and Friley, P., “A Hydrogen Economy: Opportunities and Challenges,” *Energy*, xxx. (not yet published)

34. California Environmental Protection Agency, *California Hydrogen Blueprint Plan, Volume 1 and 11, Draft Final Report,* March 2005; also, *Rollout Strategy Topic Team Report; California 2010 Hydrogen Highway Network*, January 5, 2005. Website: www.hydrogenhighway.ca.gov

35. Nemanich, G., “The Transition to Hydrogen as a Fuel,” workshop proceedings, “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future.” The Pew Center on Global Climate Change and the National Commission on Energy Policy. v**ague and overly optimistic**

APPENDIX B.
RESULTS OF THE LITERATURE REVIEWS

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** U.S. DOE, *Hydrogen Posture Plan: An Integrated Research, Development, and Demonstration Plan*, February 2004.
2. **Scenario description, if applicable**
    1. **Description of "vision," if applicable**: Need for strong Federal government role in near term, including government as early technology adopter; combination of central and decentralized production facilities, with pipelines and trucks/rail/barges distributing hydrogen; hydrogen economy, with use throughout the economy; some confusion about timeline for onsite production – time chart figure implies early production at existing central facilities with pipeline and truck/rail/barge delivery, followed by distributed onsite production at some later date…but text identifies distributed production "in the near-to-mid-term, …most hydrogen will likely be produced by technologies that do not require a new hydrogen delivery infrastructure." Milestones include technology to produce hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $1.50/kg for hydrogen (at the pump, untaxed, no sequestration, at 5,000 psi).
    2. **Dates and interval:**
    3. **Extent of focus on transition; possibly break out 2010-2030?**
    4. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** H2 consumption, H2 vehicles….but from simple stock model
    5. **Methodology: "eyeballing," stock model, historic analogy, etc.** scenarios developed with simple stock model ("VISION")
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** no
    6. **Scope: LDVs only, total transport, other sectors included** all sectors; includes stationary co-production of hydrogen and electricity, combined heat and power systems
    7. **Geographic scope: regional, national, international** national
    8. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** range of technologies; importance of developing mass-produced generators for fueling stations, with remote operations control
    9. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** none
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Strong Federal role, but not well defined….RD&D support plus technology adopter….but specific policies not stated ("government….(creates)…policies that stimulate the market")
4. **Identification of key roadblocks**
5. **Interesting results/conclusions**

6. **Comments on overall credibility (judgment by reviewer)** no real discussion of roadblocks and how to overcome them; not especially convincing

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Laitner, J.A., et al, "Adapting for Uncertainty: A Scenario Analysis of U.S. Technology Energy Futures," *Energy, Environment, and Economics in a New Era: Proceedings of the 24th Annual North American Conference of the USAEE/IAEE*, Washington, DC, July 8-10, 2004.
2. **Scenario description, if applicable**
   a. **Description of "vision," if applicable**: Baseline to 2050 based on AEO2002, with three diverging scenarios and three added scenarios that inject a climate change emergency into the other three scenarios.
      - "Cheap Energy Reigns Supreme" reflects OPEC cooperation with U.S. interests, huge increases in U.S. domestic gas production (consumption to 70 Quads in 2050!), auto fuel economy unchanged.
      - "Big Problems Ahead" reflects OPEC in conflict with U.S., terrorism, instability, intermittent cutoffs and price shocks, no coherent energy policy, low R&D….only saving grace is 2/3 of vehicle sales are fuel cell vehicles by 2050
      - "Technology Drives the Market" reflects State governments establishing an integrated set of policies that drive energy efficiency, renewable energy, distributed generation, environmental improvement. Big improvements in fuel economy, fuel cell and electric vehicles, biomass energy, etc.
      - Three "strategic challenge and response" scenarios that introduce the risk of abrupt climate change, with a portfolio of strong energy policies in each of the first three scenarios, basically similar though somewhat different in intensity.

   b. **Dates and interval:** current to 2050
   c. **Extent of focus on transition; possibly break out 2010-2030?** Focused on long-term, not on transition
   d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** GDP, energy demand, oil and natural gas imports, carbon emissions, LDV travel
   e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Scenario development and use of computable general equilibrium model, AMIGA
      - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** Not clear

   f. **Scope: LDVs only, total transport, other sectors included**
   g. **Geographic scope: regional, national, international** Focus on U.S., but AMIGA includes 22 world regions
   h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** wide range of technologies and feedstocks
   i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** One of the scenarios (Big Problems Ahead)

is essentially chaotic, with severe disruptions – unusual for scenario modeling studies

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Scenarios explore a full range of drivers
4. **Identification of key roadblocks** In some scenarios, low oil prices; lack of government incentives – no explicit consideration of hydrogen technological roadblocks that I can discern, but this is a general study, not explicitly focused on hydrogen
5. **Interesting results/conclusions**
    - **a.** Smart investment path emphasizing efficiency, advanced technologies can yield high economic growth even with high energy prices
    - **b.** Today's policy choices will affect the cost of responding to unexpected future surprises or outcomes
    - **c.** Policies to encourage capital stock turnover and accelerate commercialization of high-efficiency, low-emission technologies can significantly reduce growth in U.S. primary energy demand and CO2 emissions. (presumably there are built-in assumptions about the success of these policies)
6. **Comments on overall credibility (judgment by reviewer)**

Key uncertainty here is the degree of robustness of the modeling effort. It isn't clear to what extent the results are driven by robust modeling or, instead, by assumptions/guesses about the results of policies, effects of increased R&D. Also, I have severe doubts about resources – the domestic natural gas resources implied by "Cheap Energy" are inconceivable to me.

Hydrogen Scenarios Literature Review: Southworth, F., Pillai, R.S., and Greene, D.L., "A Hydrogen Transition Planning Model: Creating a Framework for H2 Investment Analysis and Decision-Making," Oak Ridge National Laboratory, January 21, 2004.

This paper discusses the requirements for a hydrogen transition planning model, based on a literature review that includes many of the papers reviewed for this study. It's too dense to easily summarize, but it lays out an extremely ambitious agenda for a transition model incorporating multiple feedback loops through the infrastructure investment, vehicle choice, vehicle sales, manufacturer decisions about make and model diversity, hydrogen price, and so forth. The paper implies, through a diagram of a prototype model, that the model might deal only with the LDV sector, with links to other models such as MARKAL so that it can "know" what's going on in the rest of the economy and react to that. On the other hand, the paper makes it clear that hydrogen use in the stationary market is a crucial component of any transition scenario, with the implication that it needs to be considered by the model directly. In its list of questions, it makes it clear that global interactions are crucial questions that must be modeled, presumably by ties to global models.

A few interesting points:

- The paper notes that a transition model should be able to support public policy formulation and decision-making on such policies as:
  - RD&D support
  - Legislation to advance hydrogen production and delivery systems
  - Design of codes and standard
  - Education of corporate and public opinion

  Some of these policies, e.g. RD&D support and education, are likely to be difficult to credibly model quantitatively.
- The paper lists some questions that the model should be able to address, and some of these have important implications for the structure of the model:
  - In what scenarios (under what technological and institutional conditions) will the hydrogen economy succeed? *The model could answer this in two ways: it could either start with initial conditions and then "grow" the fuel supply sector, with hydrogen either entering the system or not; or it could instead be a simpler model that started with a hydrogen scenario input to the model, calculated a "best case" for it using optimization, and then calculated costs and benefits, with the modeler deciding whether the outcome was satisfactory (e.g., benefits exceeding costs, net cash flow becoming positive within a set number of years, etc). The paper implies that the model should be able to do both (The model should be able to evaluate "both model simulated pathways and those pathways that are successful in the marketplace," e.g. the latter will be input "after the fact.").*
  - What are the costs and benefits (including global macroeconomic effects) of a hydrogen economy? *This implies some sort of linkage to a global economic model; this could be a one-way linkage, e.g. outputs of transition model fed to global model, or something more complicated and*

interactive. However, some of the model requirements clearly imply the need for interactive connections, for example, "learning" effects may well be relevant at the global level (given the global nature of the automobile industry).

Which end-use markets are currently best suited to a transition to hydrogen? *Although this obviously is a crucial question, do we really expect the transition model to answer this question? The model prototype diagram later in the paper includes only the vehicle market, but this question implies that the model addresses all demand sectors.*

The paper suggests that the market demand model capture both consumer and automobile manufacturer responses to H2 vehicle technology. This is fully in line with the Ricardo analysis, which focuses on manufacturer behavior and clearly considers this behavior as crucial to the success of any hydrogen scenario.

The paper notes that some pathways offer benefits in the short-term while others may be more expensive in the short term but offer lower cost long-term solutions. This might not be a problem for a model that simply evaluates input development scenarios, but these tradeoffs will have to be carefully dealt with in a model that chooses a solution based on external conditions such as oil prices, policies, etc.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Lipman, T., et al, *An Integrated Hydrogen Vision for California*, White Paper/Guidance Document, July 9, 2004.
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: State-driven hydrogen program, begun with experimentation with stationary and vehicle applications, followed by fleet and facility-based vehicles with local refueling, then hydrogen corridors. Early production basis is natural gas reforming. Key part of vision: don't try to "shoehorn" hydrogen into inappropriate roles, systems that aren't ready – identify key niches and roles for hydrogen that improve the potential performance and economics of these systems.
    b. **Dates and interval:** initial stage through 2008 or later, includes initial hydrogen corridors (up to 1,000 vehicles, 50-60 refueling stations); growth stage 2008-2011+ includes expansion in stationary applications, refueling infrastructure spreads beyond key corridors into broader networks across more of the State (up to 20,000 vehicles, 100+ refueling stations); maturation stage post 2012, triggering of refueling requirements in major outlets, hydrogen becomes available at 10-20% of refueling outlets.
    c. **Extent of focus on transition; possibly break out 2010-2030?** Focus is primarily on transition, current – 2017 or so
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Not a quantitative analysis, no specific scenario development
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** not described
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** no
    f. **Scope: LDVs only, total transport, other sectors included** transport plus stationary
    g. **Geographic scope: regional, national, international** California plus neighboring states
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Begins with natural gas, then renewables
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability**
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** public/private partnerships, State ZEV mandates, State fleet purchases, subsidies for refueling stations, strong government focus on codes and standards
4. **Identification of key roadblocks** cites National Research Council report; concern about potential for stranded assets
5. **Interesting results/conclusions**

6. **Comments on overall credibility (judgment by reviewer)** This is purely a vision statement without analysis, so it's hard to judge its credibility. It does seem optimistic, with a very short timeline for building multiple stations despite its professed concern about stranded assets and the remaining concerns about extremely high vehicle prices, likely high fuel price, and other roadblocks.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable**
   - Ogden, J. and Kaijuka, E., "New Methods for Modeling Regional Hydrogen Infrastructure Development," presentation to National Hydrogen Association Meeting, Washington, DC, March 5, 2003
   - Ogden, J., Research at UCDavis on Design and Analysis of Hydrogen Distribution Infrastructure, presented to Fuel Pathways Technical Team, Oct 14, 2004
   - Yang, C., "Integrated Infrastructure Transition Modeling for a Hydrogen Economy," Hydrogen Systems Modeling Workshop, Sept 20, 2004
2. **Scenario description, if applicable**
   1. **Description of "vision," if applicable**: Given rate of hydrogen penetration in a city, find the least-cost transition path, define what the infrastructure looks like to satisfy some minimum requirements, define when a transition from distributed to central production should take place. *The described modeling appears to start with a scenario of hydrogen penetration and compute what that would look like, rather than how outside conditions will affect whether and how fast hydrogen market growth would occur.* ***In other words, this is normative modeling.***
   2. **Dates and interval:** 2010-2070+, appears to be calculated in yearly intervals
   3. **Extent of focus on transition; possibly break out 2010-2030?** Primary focus on transition, crossover from distributed to central H2 production
   4. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price**: Optimal system design (e.g., pipeline routes for specific case studies, # of refueling stations, etc), cash flow (given H2 price), resource use (e.g. coal use, natural gas use, electricity use), delivered H2 cost, CO2 emissions and avoided emissions, investment cost
   5. **Methodology: "eyeballing," stock model, historic analogy, etc.** Extensive transition modeling/analysis, including:
      1. Infrastructure costs calculated as function of city geographic factors, H2 market size, etc.; modeling methodology not clear from presentations, clarity awaits publication of papers, but claim of system optimization for least cost
      2. Geographic Information System analysis of station siting
      - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No
   6. **Scope: LDVs only, total transport, other sectors included** Highway vehicles
   7. **Geographic scope: regional, national, international** City
   8. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies**: Natural gas, coal, biomass, wind, solar; production technologies are natural gas steam reforming and electrolysis for central

and distributed, other central technologies are coal gasification with and without sequestration, biomass gasification, H2/electricity co-production

   i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability**

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Presentations discuss future analysis of the impact of policy, feedstock prices, technology changes. *Current analysis assumes hydrogen penetration and searches for the best means to achieve it, rather than examining how conditions will affect hydrogen market entry and growth*…if this approach continues, analysis of key drivers will affect the computed approach and costs
4. **Identification of key roadblocks** not discussed
5. **Interesting results/conclusions** Analysis of specific case study cities, States, e.g. Ohio; in Ohio, repowering of existing coal-fired powerplants with gasification could yield satisfaction of electricity demand plus H2 for 2.5 million fuel cell vehicles (29% of LDV fleet); other results:
   a. It can make sense to start with distributed production, then switch to central plant production
   b. Rapid growth of H2 demand lowers transition costs, CO2 emissions over time
6. **Comments on overall credibility (judgment by reviewer)** Presentations give the strong impression of a detailed and thoughtful effort….but not enough detail to judge further.

Hydrogen Scenarios Literature Review: Ogden, J., “Hydrogen Systems Modeling: a) Transition Modeling: Early Results; b) Observations and Research Questions; c) Thoughts on the State of the Art,” presented at the Hydrogen Pathways; Hydrogen Systems Modeling Workshop, UCDavis, Sept 20-12, 2004.

Description only of topics relevant to transition modeling:

1. Consensus/debate among modelers:
    a. Hydrogen transitions will take decades
    b. Transitions will be costly, but same order of magnitude of projected oil and gas infrastructure investments (my comment: only if reference case applies to oil and gas – strong efficiency efforts could substantially decrease oil and gas infrastructure requirements….gets to the question about what the correct comparison scenario is)
    c. Substantial time before anybody profits, though time and investment costs extremely variable – implies need for understanding decision rules of various investors, and having a model that can track each investor/actor
    d. Large geographic variations
    e. Interaction with rest of energy system is important (so need some link to stationary hydrogen uses, energy prices in the economy and the effect of hydrogen use on these prices, possibly world energy market)
2. Multiple model types for transition: engineering/economic system design, lifecycle assessment, planning/urban design, equilibrium energy system model, system dynamics, agent-based models, integrated assessment
3. Modeling hydrogen demand is difficult
4. Key modeling questions:
    a. Boundary drawing (same issue as how to deal with interaction with rest of energy system)
    b. Demand for hydrogen
    c. Consumer behavior, behavior of other agents
    d. Market dynamics
    e. Level of complexity needed (tradeoff between being able to model a complex system and problems of our actual understanding of all the interactions, analytic costs – including need to deal with a large volume of input data)
5. Summary of various presentations:
    a. Christopher Yang
        i. Demand profile is critical determinant of hydrogen cost and optimal transition year
        ii. City size another important determinant
    b. David Hart (Imperial College, London

    i. Larger plants require fast demand ramp-up (to help pay capital costs), difficult with high cost vehicles
    ii. Delivery fleets have short lives, favor low capital cost vehicle (Is this about current rapid turnover of such vehicles or harsh operating environment? Could fleets adjust their business practices to deal with high capital cost vehicles?)
    iii. Lack of resale market can be a major problem (same issues as above ii)
    iv. Planning issues and land availability will affect infrastructure development in cities (presumably this is about the idea that large dense cities can support central plants from a demand density standpoint, but can the pipelines be laid and service stations built in developed cities?)
    v. Infrastructure type depends on demand ramp-up rate (same as i?)
c. Stephan Unnasch, TIAX
    i. Early transition costs can be low (mobile fuelers), but eventually infrastructure investment gets risky with potential for stranded assets
d. Sandy Thomas, H2Gen
    i. Renewable hydrogen from ethanol is least costly renewable option
    ii. Need to identify consumer valuation of hydrogen FCV
e. David Greene, et al, HyTrans
f. Conzelmann, ANL
    i. Agent-based complex adaptive systems approach
    ii. Models heterogeneity of market participants (which deals with the issue of capturing the different requirements of the various actors)
    iii. Focuses on transition, designed to gain understanding of causes and drivers
    iv. Market-specific criteria for different energy markets (for example, appropriate discount rate for vehicle manufacturer may be different from that of fuel provider)

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Eyre, N., Fergusson, M., and Mills, R., *Fuelling Road Transport: Implications for Energy Policy*, Energy Saving Trust/Institute for European Environmental Policy/National Society for Clean Air and Environmental Protection, November 2002.
2. **Scenario description, if applicable**
   a. **Description of "vision," if applicable**: The scenarios are combinations of three types of scenarios – transport demand, vehicle technology, and energy scenarios:
      - **Transport demand**
        1. Baseline – business as usual, with traffic growth trailing off in mid-term to reflect capacity constraints and saturation. Heavy goods traffic grows strongly.
        2. World markets – globalized future with fast growth and growing mobility
        3. Global sustainability – societal action to curb adverse effects, with lower traffic growth, mode shifts
        4. Central case – composite vision with some slowdown in car use over baseline, but otherwise similar.
      - **Vehicle technology**
        1. Limited progress, only modest technical change except dieselization
        2. Moderate progress
        3. Rapid progress -- with early introduction of hybrids and then fuel cells for cars, buses
        4. Biomass alternative -- with a rapid switch to methanol, not to hydrogen fuel cells; 50% of new cars on direct methanol fuel cells by 2050.
        5. Combined H2/methanol, with hydrogen in passenger vehicles and methanol in goods vehicles.
      - **Energy**
        1. Business as usual – lots of oil and gas use, with hydrogen only from gas; coal and nuclear electricity eventually phased out; 20% renewable electricity by 2050.
        2. High renewables – mostly about renewable *electricity*, with nearly 100% by 2050; mostly gas for hydrogen production, moderate alcohol additives to highway fuels
        3. Electrolytic hydrogen – hydrogen from electricity exclusively, after 2020; high renewable electricity, magnitude as in "High Renewables."
        4. High biofuels – woody biomass for methanol and ethanol by 2020; limited hydrogen from woody biomass; natural gas is primary electricity feedstock.

   b. **Dates and interval:** 2000-2050, with focus on 2010, 2020, and 2050

  - **c.** **Extent of focus on transition; possibly break out 2010-2030?** Results do have a separate focus on early transition period, but there is no discussion of transition issues. No discussion of any analysis of the realism of the transition, e.g. evaluation of cash flow.
  - **d.** **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Primary energy use, Final user energy, carbon emissions
  - **e.** **Methodology: "eyeballing," stock model, historic analogy, etc.** Scenarios are constructed based on previous studies, with major variables (car and other mode use, % penetration of vehicle technologies over time into new vehicle fleet, % useage of biofuel additives, % feedstock sources for hydrogen production) all exogeneously specified; stock model and well-to-wheels calculations derive energy and carbon emissions results. **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids**
  - **f.** **Scope: LDVs only, total transport, other sectors included** Focus on transport
  - **g.** **Geographic scope: regional, national, international** United Kingdom
  - **h.** **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Full range of feedstocks
  - i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** No

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Since all major variables are exogeneously supplied, there are no *analytic* drivers. The scenarios do postulate a wide range of drivers – public attitudes towards environment; globalization; government policy; technological progress – but, again, all key variables are simply specified rather than derived from "initial conditions."
4. **Identification of key roadblocks** No discussion of roadblocks
5. **Interesting results/conclusions**
  - **a.** It makes sense to move forward with natural gas as a hydrogen source, because "any hydrogen production could be designed to draw on a range of different fuels quite quickly in the event of external disruption to gas supplies." *Perhaps true only if the hydrogen were produced in central facilities, which could be adapted to other feedstocks. With gas station hydrogen production, which might be the most logical early system structure, adaptation to other feedstocks seems unlikely.*
  - **b.** Of the two key areas of energy insecurity – concentration of power in the hands of a few oil exporters, and potential for short term disruptions – none of the examined scenarios, which cover a wide range of possibilities, offers much insurance against a disruption in the short term beyond the possibilities of bi-fuel vehicles. In the longer term, hydrogen use with multiple feedstocks does guard against such a disruption.

c. **There are no carbon benefits in producing hydrogen for use in transport from renewable electricity.** This is because, for the United Kingdom's electric system, using the renewable electricity to instead substitute for natural gas-based electricity (which would be the marginal electricity producer) would save ~ 100 grams of carbon/kWh vs. 60 gC/kWh to displace diesel fuel in a diesel hybrid. **Note here that it is crucial to compare transport hydrogen use to competing uses for the feedstock; also, the baseline vehicle technology is crucial to the calculation.** Using diesel hybrids as the baseline appears to make perfect sense for the UK, because diesel is strong *and* because a world where hydrogen fuel cell vehicles make sense is also a world where hybrids make sense. Note that the renewable electricity being talked about here is windpower, solar, or hydro, not biomass-generated electricity (because biomass use as a feedstock for hydrogen production would make most sense as a gasifier feedstock, not a feedstock for electricity to electrolysis production of hydrogen). Were low carbon electricity sources the actual marginal sources, this conclusion would change. Such sources include renewable electricity, nuclear, fossil with sequestration, and natural gas electricity generation at efficiencies above 80%, meaning combined heat and power (CHP).

d. The conclusion about renewable electricity producing hydrogen as not being the best use would change if the transport use of hydrogen gives rise to additional demand for investment in renewables, so that new grid connected renewable electricity sources are developed and utilized specifically as a result of an additional market in transport. *The implication here is that fuel cycle evaluation of hydrogen and competing technologies would benefit from a careful examination of the context and any secondary effects of implementing the technologies.*

e. For long distance shipping of energy, hydrogen competes well with electricity and the economies of scale of hydrogen transportation are likely to be better – in other words, if one has the choice of generating renewable electricity at a remote location and either shipping the electricity to electrolyzers at the market location or shipping the hydrogen after producing it at the generation site, shipping the hydrogen is a good alternative.

f. A viable option for using biomass as a fuel cell energy feedstock is to first produce bioalcohols and distribute these to stations for reforming into hydrogen, or directly to vehicles for onboard reforming or (with methanol) for direct use in a fuel cell. *A particular benefit of producing bialcohols is that "they offer a clear and technically feasible alternative path to a renewable transport fuel system even if hydrogen fuel cells prove not to be viable."*

g. For the UK, woody fuels might supply 50% of current transport fuels demand using lands with poorer quality than required for food crops. In contrast, annual biofuel crops would require far more land, and that land would have to be of higher quality.

   h. No doubt that hydrogen from biomass will be cheaper than hydrogen from electricity.
   i. Using woody biomass to manufacture hydrogen (or alcohol) for use in an efficient fuel cell vehicle has comparable carbon benefits to using biomass for CHP, and probably larger benefits than using biomass for either heat or power generation alone.
   j. Developing a hydrogen infrastructure will be exceedingly costly if it is done rapidly, replacing assets before the end of their natural lifetimes. Hydrogen from natural gas therefore seems likely to provide "a step on the route to a slower and more economically acceptable transition to hydrogen vehicles."

6. **Comments on overall credibility (judgment by reviewer)** This study seems carefully done with multiple scenarios. One concern is that many comparisons are generated in areas where technical uncertainty is quite high, but definitive answers are given without parametric examination of the uncertain variables. Also, it must be remembered that the key variables are generated by assumption rather than analysis, that is, things like fuel cell vehicle penetration rates, yet there is no apparent attempt to subject the scenarios to reality tests such as examinations of cash flows.

Hydrogen Scenarios Literature Review of *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Academy of Engineering, Board on Energy & Environmental Systems, 2004. (Presentation by M. Ravage, February 4, 2004), plus some reading of the full report.

Vision: The very early transitional program will probably be fueled by pressurized or liquefied hydrogen being trucked from existing, centralized facilities. Then, distributed systems will take hold, primarily natural gas reformers to supply hydrogen; urges DOE to focus research on small appliances, including electrolysis (these need breakthroughs). Some possibilities for early use of renewables in distributed production, especially wind-powered electrolysis – could play a key role in transition. Foresees large penetration of ICE hybrids (60% penetration of new vehicle fleet by 2024), then superceded by hydrogen FCVs.

Key transition conclusion: "There will likely be a lengthy transition period during which fuel cell vehicles and hydrogen are not competitive with internal combustion engine vehicles." ***Obvious implication is that either government or private industry, or both, will have to subsidize hydrogen development for a number of years for such development to succeed.*** **The further implication is that a model must be capable of adequately modeling the impacts of various types of subsidy programs, since these will have to be an integral part of any hydrogen transition.**

Stress high risk of failure; during past 20 years, most alternative fuel programs have failed.

Natural gas reforming of questionable applicability to long term, given supply from imports

Judges delivery and vehicle storage problems as "formidable" – pipeline delivery difficult because of embrittlement, propensity to leak; onboard storage difficult because of energy, space, cost, and weight problems with both compressed and liquid hydrogen.

Believes pressurized or liquid onboard storage can't meet DOE energy density target, suspects safety of high pressure storage may be an important issue; focus on alternative storage systems (what about "superefficient ultralightweight vehicle?).

For transition:

- **Niche markets are crucial**
- **Government as first customer?**
- **Safety must be removed as an issue**
- **Key question: What incentives will entrepreneurs and investors need before they will commit capital?**

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Lovins, A.B. and Williams, B.D., "A Strategy for the Hydrogen Transition," 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, Virginia, April 7-9, 1999.
2. **Scenario description, if applicable**
   a. **Description of "vision," if applicable**
      - Fuel cells first move into **buildings**, especially those where new electric infrastructure would otherwise be needed, using hydrogen from mass-produced appliances (electrolyzers or natural gas steam reformers). The hot water produced by fuel cells can be used for heating, cooling, and dehumidification. Customers benefit from enhanced reliability and excellent power quality.

      Production volume from use in buildings reduces costs, improves performance for introduction into **extremely efficient vehicles**, focusing especially on vehicles whose owners work or live in or near the buildings. Ultra-high efficiency (carbon-fiber bodies, etc) solves on-board storage problem, since less fuel is needed, and allows small fuel cells to be used, reducing costs further. Additional benefits gained from using vehicles as a generating asset, sending electricity back to the grid during peak periods.

      Growing market yields incentives for free-standing fuel stations and bulk supply options
   b. **Dates and interval**: near-term, e.g. next 10-20 years
   c. **Extent of focus on transition; possibly break out 2010-2030?**: almost exclusively on the transition
   d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Virtually no quantification of these variables. Paper seems to treat likely hydrogen price as competing with gasoline on an energy-services-delivered basis, e.g. high because hydrogen system is postulated to produce extremely high efficiencies (yielding large incentives for hydrogen producers)
   e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Basically a "vision" argument supplemented by multiple estimates/calculations of efficiencies, costs, etc. of hydrogen and gasoline systems. No models used/no formal analysis.
      - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** Some consideration of EVs, methanol, CNG vehicles
   f. **Scope: LDVs only, total transport, other sectors included** LDVs, some trucks and buses, buildings
   g. **Geographic scope: regional, national, international** Focus is really at the local level, with some discussion of regional differences
   h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Focus on distributed electrolyzers and natural gas steam

reformers; some discussion of larger scale technologies, e.g. hydro and wind with hydrogen storage, natural gas wellhead reforming with sequestration

- i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** None

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Key driver is the development of ultra-efficient vehicles, which greatly reduce some of the concerns about hydrogen vehicles (esp. fuel storage, system cost), and pursuit of the scenario vision; the paper basically concludes that technology breakthroughs and strong government programs aren't necessary, that technology improvements required are those that will come naturally with growing production. However, carbon credits would certainly be useful.
4. **Identification of key roadblocks** None except perhaps lack of vision.
5. **Interesting results/conclusions**
    - No real technology breakthroughs are needed for a successful hydrogen economy
    - Integrating hydrogen use in buildings and vehicles yields substantial benefits, cost reductions
6. **Comments on overall credibility (judgment by reviewer)**

The scenario/vision of this paper is both brilliant and extremely problematic, primarily because of the details (see J. Wilson's paper). Some problems:

- Quantification of hydrogen's competitiveness in vehicles compares ultra-efficient hydrogen vehicles with gasoline in conventional vehicles, ignoring the obvious fact that development of the former will create far more efficient gasoline vehicles, for example greatly reducing the cost of hydridization
- Many of the hydrogen efficiency calculations in the paper appear extremely optimistic, probably leave out important sources of energy losses such as accessory and parasitic losses in fuel cell vehicles, AC/DC conversion, electric motor losses, etc. On the other hand, efficiency values given for gasoline systems seem very low, especially for the newest vehicles and future vehicles.
- Safety concerns are minimized, e.g. need for very careful maintenance and monitoring of thousands of small reformers.
- Overconfidence about lack of need for technological breakthroughs, both in ultralight vehicles and in fuel cells (reliability and durability are major concerns).
- The early vision of vehicles refueling at workplace/living place ignores need for refueling for out-of-area travel.

Hydrogen Scenarios Literature Review: Sperling, D. and Cannon, J.S., *The Hydrogen Energy Transition: Moving Toward the Post Petroleum Age in Transportation*, Elsevier Academic Press, 2004

Chapter 12, "Lessons Learned from 15 Years of Alternative Fuels Experience – 1988 to 2003," McNutt, B. and Rodgers, D.

1. Conventional vehicle/fuel industries will compete vigorously, so altfuel vehicles have to be significantly better and stay better as conventional vehicles improve
2. Niche markets don't necessarily grow into mainstream markets
    a. Fleet vehicles didn't match needs of general consumers
    b. Tradeoffs acceptable to fleets, e.g. limited range, were unacceptable to general consumers
    c. Limited engineering resources available for emissions testing and certification, limited models available
3. FLEETS
    a. Most light-duty fleets are no longer centrally fueled, less attractive altfuel targets
    b. Fleets want low operating costs, are *very* resistant to expensive fuels and especially to expensive vehicles
    c. Centrally fueled fleets often can buy conventional fuel in bulk, at lower prices
    d. Fleets tend to have longstanding relationships with vehicle and engine suppliers that are not easily dissolved
    e. Fleet vehicle turnover is high, so they need a robust resale market
    f. Labor costs for extra driving time to find a refueling station and extra refueling time can swamp any fuel cost savings
4. Early builders of refueling stations have usually been disappointed
5. Transition technologies can become so good as to overwhelm the end point technology
    a. FFVs over dedicated vehicles
    b. Reformulated gasoline over methanol
    c. HEVs over EVs
6. The current vehicle/gasoline system has enormous economies of scale
7. Federal fleet requirements are too small and too varied to provide significant economies of scale
8. Conclusion: infrastructure development for hydrogen will require a strong and long-term government role

Chapter 14, "Understanding the Transition to New Fuels and Vehicles: Lessons Learned from Analysis and Experience of Alternative Fuels and Hybrid Vehicles," Leiby, P. and Rubin, J.

1. Conclusions of existing models of altfuels penetration reflect exogeneous assumptions regarding fuel and vehicle prices or AFV penetration or both
2. TAFV – *determines* fuel and vehicle prices and penetration rates from market conditions. The model tries to satisfy final demand for transport services determined for AEO projection of LDV fuel use (my question: since each vehicle/fuel combination has different efficiencies, is the model trying to satisfy demand for fuel/Btus or demand for **vmt**? Modeled barriers:
    a. Consumer cost of limited fuel infrastructure and retail availability
    b. Economies of scale
    c. Cost of limited model choice and diversity
    d. Technological improvement and cost reduction through learning by doing
3. Transitional barriers, and the particular transition paths pursued, matter a lot for the technology's ultimate market success."
4. There is a strong conflict between diversity of choice and cost savings from economies of scale in vehicle production and network economies for fuel provision…….so there's a major tension between the merits of producing different AFV technologies for different circumstances and for different consumer regions or market segments, and the substantial scale and network economies associated with producing and fueling and fueling a single vehicle-fuel technology
5. Niche introduction to fleets hasn't worked in the past…but niche applications can be an effective strategy if one anticipates substantial technological learning by doing…..relevant to hydrogen.
6. Note: "forgetting" can also occur, as well as learning; production experience can depreciate over time…..."Learning is very tricky to represent."
7. **"Little rigorous analysis of alternative ways the transition to hydrogen could take place."**
8. Important issues for modeling a hydrogen transition: interactions with other energy sectors and the spatial and geographic detail in the location of production, delivery, and demand.

Hydrogen Scenarios: Literature Review of: Tyndall Centre report

1. **Full citation, including web site if applicable:** Dutton, G., et al, *The Hydrogen Energy Economy: Its Long-Term Role in Greenhouse Gas Reduction, Tyndall Centre Technical Report 18, January 2005, United Kingdom*
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable:** 4 scenarios, with 2 variables (individuals/consumers vs. community, regionalization vs. globalization). The scenarios are World Markets (integrated economies, focus on low energy prices); Provincial Enterprise (regional focus, low energy price focus); Global Sustainability (integrated, high environmental consciousness); Local Stewardship (regional focus, environmentally conscious)
    b. **Dates, e.g. 2000-2050, and interval (5 year, 10 year, etc):** 2000-2050; analysis is annual, but results given in 10 year increments
    c. **Extent of focus on transition; possibly break out 2010-2030?** Analytic concern about dates of technology introduction and rates of increase, but no formal analysis of transition
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** CO2 emissions; total transport energy use; % H2 vehicles; H2 production capacity
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Overwhelmingly based on judgment, with some use of accounting models, e.g. vehicle stock model. Scenario inputs based on judgment are economic and energy growth rates, energy intensity changes, H2 technology penetration by sector, type and character of new electric capacity, type and character of H2 production. Accounting models calculate electricity and fuel demands, power station stock, CO2.
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No, but authors recognize potential for competition
    f. **Scope: LDVs only, total transport, other sectors included** All sectors, but real focus is on transport and electricity supply
    g. **Geographic scope: regional, national, international** United Kingdom, with ROW (rest of World) assumed to be subject to same forces
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Basically all feedstocks and production technologies
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** None
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Scenario assumptions are translated into judgments about key energy inputs; some drivers are discussed in scenario descriptions, but not a factor in analysis

4. **Identification of key roadblocks**
   Liquefaction energy ~ 35% of H2 energy, with R&D goal of 20%
   Electricity and biomass can be H2 competitors, e.g. EVs and biomass liquids
5. **Interesting results/conclusions**
   - **a.** In the World Markets scenario, electricity supply is dominated by natural gas and coal (because of low environmental consciousness), but low H2 production and use
   - **b.** A hydrogen economy is a high energy economy, because hydrogen production and distribution is energy intensive
   - **c.** Implementation of a hydrogen economy has only a modest effect on natural gas supply, because high H2 is compatible only with a desire for low CO2 emissions, thus an emphasis on renewables and perhaps nuclear…BUT if H2 demand expands rapidly and renewable and nuclear capacity can't keep up, gas-driven SMR might be pushed into service
   - **d.** Analysis needs to account for the role of consumer behavior
   - **e.** Also need to account for the role of oil price shocks
6. **Comments on overall credibility (judgment by reviewer)**
   Completely based on expert judgment, without much quantitative analysis, except for "accounting"

Hydrogen Scenarios Literature Review:

7. **Full citation, including web site if applicable** Lasher, S., Unnasch, S., and Chan, M., "Hydrogen Infrastructure: Energy, Costs, and Transition," 2004 Fuel Cell Seminar, San Antonio, TX, November 1-5, 2004, TIAX LLC; also, Unnasch, S., "Hydrogen Transition Model H2NowNPV," Hydrogen Systems Modeling Workshop, UCDavis, September 20, 2004 (Powerpoint presentation); also, Lasher, S., "Fuel Choice for FCVs: Hydrogen Infrastructure Costs," DOE Merit Review, May 25, 2005, powerpoint presentation.
8. **Scenario description, if applicable**
   a. **Description of "vision," if applicable**: Normative scenario, starting with assumption about vehicle penetration, analysis determines number of stations, production facilities, costs, and benefits. Fast and Slow (30% by 2050) Introduction Scenarios; President's Initiative as a sensitivity case; high fuel economy case (both gasoline ICEVs and H2 FCVs)
   b. **Dates and interval:** 2003-2063
   c. **Extent of focus on transition; possibly break out 2010-2030?** Fast transition about 2007-2023, slow about 2007-2035
   d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** GHG emissions; energy use; hydrogen price; # of fueling stations; cumulative investment in infrastructure; hydrogen revenue
   e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Examination of infrastructure cash flow is a particular focus, especially examining negative cash flow; key assumption is that H2 is priced at gasoline $/mile equivalent. H2A capital and operating costs for *long-term* station costs. 2005 presentation includes GREET for GHG inputs.
      - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** Apparently not
   f. **Scope: LDVs only, total transport, other sectors included** LDVs only
   g. **Geographic scope: regional, national, international** National; presentation mentions examination of consecutive regional roll-in of FCVs, starting with West Coast
   h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Transition production is natural gas/steam reforming and decentralized electrolysis; variety of feedstocks for later; presentation focuses on natural gas/steam reforming, including mobile fuelers that can be moved from region to region as scenario develops (2005 presentation includes excess or "moth-balled" merchant, ammonia, refinery, and methanol plant hydrogen capacity).
   i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability**
9. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices**

10. **Identification of key roadblocks**
11. **Interesting results/conclusions** For a slow transition, it takes 40 years and $50 billion investment before a simple payback is achieved (in 2005 presentation, NPV goes positive by ~50 years); fast transition allows very little negative cash flow, breakeven by 2023 and rapid buildup of positive cash flow; “relatively modest investment is required to achieve a 10% fueling station coverage with cheap distributed infrastructure” (presentation). Fast transition would require significant market drivers (but so would a slow one). The major financial risks could be low in the short-term with mobile fuelers, but over the long-term, potential for stranded assets is high. Use of existing hydrogen capacity for the transition is interesting, but will be hampered by high transportation and feedstock costs.

    Slow introduction of hydrogen vehicles will do little over the next 50 years; and fast introduction will take 25+ years to see a significant impact.

    Investment risks are high for all stakeholders!
12. **Comments on overall credibility (judgment by reviewer)** Need further details

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Millett, S. and Mahadevan, K., "Commercialization Scenarios of Polymer Electrolyte Membrane Fuel Cell Applications for Stationary Power Generation in the United States by the Year 2015, Battelle Memorial Institute; and same authors, "PEM Fuel Cell Scenarios to 2015, Powerpoint presentation, November 3, 2004.
2. **Scenario description, if applicable** 5 scenarios: commercial disappointment; qualified success in residential and light commercial applications; roaring success; success with a hydrocarbon infrastructure; qualified success in commercial and office building applications.
    a. **Description of "vision," if applicable**:
    b. **Dates and interval:** current to 2015
    c. **Extent of focus on transition; possibly break out 2010-2030?**
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** fuel cell investment and sales, scenario probability
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Interactive Future Simulations model; scenario descriptors defined by expert judgment, each with alternative outcomes that are mutually exclusive and exhaustive, descriptor outcomes and cross-impact matrix defined by expert judgment.
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** Conventional fossil alternatives
    f. **Scope: LDVs only, total transport, other sectors included** stationary fuel cell markets; automotive applications is a descriptor, with the extent of the automotive market affecting other determinants of stationary market development (but connection between stationary and automotive applications is not described)
    g. **Geographic scope: regional, national, international** national
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** not clear
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** probability analysis
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** 28 descriptors/drivers
    a. Retail price of PEM fuel cell system
    b. Prevailing system architecture of PEM fuel cell
    c. Retail cost of PEM fuel cell reformer
    d. PEM fuel cell system ease of installation
    e. Consumer market image of PEM fuel cells
    f. Magnitude of PEM fuel cell investments in the US
    g. Nature of PEM fuel cell manufacturing

- h. PEM fuel cell technical advances
- i. Hydrogen fuel sources
- j. Fossil fuel and engine/turbine technical advances
- k. Advances in electric storage technologies
- l. Stringency of environmental regulations
- m. Adequacy of codes and standards for PEM fuel cells
- n. Degree of public policy support for fuel cells
- o. Strength of national energy policies
- p. Electric grid reliability and quality
- q. Role of distributed generation in power grid
- r. Grid electricity prices
- s. PEM fuel cell operating costs
- t. Oil and natural gas prices
- u. Impact on U.S. of overseas deployment of stationary fuel cells
- v. Electric utility industry structure
- w. Competitors to PEM fuel cells
- x. Degree of penetration of PEM fuel cells into vehicle markets
- y. Extent of PEM fuel cell penetration into power applications
- z. Primary customers of PEM fuel cells
- aa. PEM fuel cell market size, $

4. **Identification of key roadblocks**
5. **Interesting results/conclusions** High degree of success dependent on multiple conditions:

   Fully integrated fuel cell unit, with plug-n-play (inexpensive) installation
   Fuel cell image is important: “hi tech”
   Substantial technical advances needed
   Fuel infrastructure crucial, fuel competitively priced as commodity fuel
   Comprehensive, aligned codes and standards
   Substantial government support needed
   High electric grid prices
   Operating costs can be in medium range (10-20 cents/kWh)
   Need residential and light commercial market

   Point of market entry may be the isolated and high-value applications, followed by use as back-up and peak shaving power generation for commercial and office building customers
6. **Comments on overall credibility (judgment by reviewer)** Conditions for full success seem excessive, unrealistic

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Thomas, C.E., Hydrogen Transportation Transition Pathways," Hydrogen Systems Modeling Workshop; Hydrogen Pathways Program, UCDavis, Sept 20,2004, Powerpoint Presentation
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: Basically a largely static analysis of technology/resource pathways, focusing on advantages of distributed H2 production from natural gas feeding first into H2 ICEs, eventually into fuel cells, with H2 production moving to renewables when they are ready.
    b. **Dates and interval:** 2000-2100; graph points at 1 year intervals
    c. **Extent of focus on transition; possibly break out 2010-2030?** Infrastructure investments begin before 2010, peak around 2023; no focus on specific time paths, though, that is, how things develop over time
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** H2 infrastructure investments, oil import savings, pollution reductions (CO, GHGs, NOx, VOCs)
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Methodology for roll-in not described; extensive cost analysis of competing H2 supply options, vehicle options
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** HEVs only
    f. **Scope: LDVs only, total transport, other sectors included** LDVs
    g. **Geographic scope: regional, national, international** National, California
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** All
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability**
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** *Not a scenario analysis per se, no drivers….just a comparison of costs and benefits given hydrogen penetration, then an examination of scenarios that postulate 100% penetration of competing technologies within a 100 year timeframe.*
4. **Identification of key roadblocks**
5. **Interesting results/conclusions**
    a. HGM (Hydrogen Generating Module) on-site natural gas system provides lowest H2 costs (~ \$2.85/gge) for natural gas price of \$6.23/mmBtu; everything else is much more expensive either because of high delivery costs or high equipment costs/low efficiency.
    b. Electrolyzer issue: using cheap off-peak electricity saves less money than added by higher capital recovery costs (since only use equipment part of the day, need larger electrolyzer) – so count on average electricity costs for electrolyzers

- **c.** Gauging marginal electricity mix (thus, GHG emissions) for electrolyzers can be tricky. Example shows that increasing renewables can shift coal from baseload only (implying all marginal electricity will come from natural gas) to load-following, implying some marginal electricity will come from coal….so (in this example) although overall GHGs from electricity may be down in the "higher renewables" case, GHGs from electrolyzers may be higher.
- **d.** Compared to gasoline ICEV GHG emissions, electrolytic H2 using marginal US grid mix nearly doubles emissions; SMR natural gas to compressed H2 in fuel cell yields 45 to 50% reduction; SR ethanol from biomass to H2 fuel cell yields 60-85% reduction
- **e.** Renewables reduce more GHGs in grid displacement than gasoline displacement via H2 production
- **f.** **Fuel costs/mile:** compared to gasoline ICEV @ ~ 8 cents/mile, ICE HEV @ 6, H2 from NG to ICE HEV @ ~ 5, H2 from NG FCV @~ 3-4….but other options with H2 are more expensive…cheapest is H2 from ethanol to FCV @~ 9 (I assume this has an onboard reformer….presentation doesn't say)
- **g.** Maximum market penetration rates will vary substantially by technology, with gasoline HEV fastest, H2 ICE HEV next, H2 FCV next, renewable H2 slowest (presumably because H2 supply comes on slowly)
- **h.** **Scenarios:** gasoline HEVs will reduce future GHG emissions, but cannot outrun growth in travel demand; hydrogen from NG in HEVs can provide virtually the same GHG emission reductions as H2 from NG in FCVs; can use them as an affordable bridge to renewable H2 in FCVs.

6. **Comments on overall credibility (judgment by reviewer)** Author is a well-established analyst; key issue is costs of small SMR NG units, as the author is the president of a company that manufactures them.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Thomas, C.E., James, B.D., and Lomax, F.D. Jr, “Market Penetration Scenarios for Fuel Cell Vehicles,” *Int. J. Hydrogen Energy*, Vol. 23, No. 10, pp. 949-966, 1998.
2. **Scenario description, if applicable**
    a. **Description of “vision,” if applicable**: Scenarios postulate early government investment that lowers costs to create an incentive for vehicle manufacturers and energy companies to invest in FCVs and hydrogen infrastructure. Both pure hydrogen FCVs and reformer-equipped FCVs are examined.
    b. **Dates and interval:** 2005-2030, 1-year intervals
    c. **Extent of focus on transition; possibly break out 2010-2030?** In this case, transition is projected to happen quickly, so infrastructure investment peaks around 2020 or so. The focus here is on examining industry investment and profits to check whether the transition is viable. The transition is dealt with by starting with factory-built small-scale hydrogen appliances (reformers and electrolyzers) that can be easily and quickly installed in multiple sites.
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** # of fuel cell vehicles; FCV cost; FCV investment and profit; hydrogen production and price; infrastructure investment; hydrogen fuel retailer annual revenue and expenses; public costs and benefits.
    e. **Methodology: “eyeballing,” stock model, historic analogy, etc.** The number of FCVs sold each year is determined by price elasticity curves for vehicles and hydrogen, with hydrogen and FCV cost varying with production based on “progress ratios” that track cost reductions as production doubles and doubles again (an interesting feature of the progress ratios for vehicles is that they are company-specific – it is assumed that most of the gains are obtained by individual companies according to the number of vehicles they each produce, not as an industry-wide phenomenon). There are two markets for vehicles – one ZEV market (based on now –superseded California regulations) and one conventional market. Paper does not describe how the price elasticity curves are derived. FCV component and hydrogen production costing is based on a detailed costing analysis in cooperation with Ford. Analysis estimates number of FCVs within range of fueling stations, given assumed station spacing, which determines the type of station (four sizes assumed, with specific technologies for each) and hydrogen production technology used, thus costs (for California and other “opt-in” States).
    Paper mentions market penetration scenarios including a list of government actions, but it is not clear what these scenarios are or how they are used in the analysis, no indication of how most of the actions on the list are used in the scenarios. (There is an apparent disconnect between the statement that “key input variables to the model include

vehicle market scenarios and government actions" and the apparent reliance on simple price elasticity curves for FCVs and hydrogen, which would seem to determine a "market scenario" without any connection to government action. There is some evidence that what the paper means by "vehicle market penetration scenarios" is really just estimates of vehicle costs, which in turn will determine penetration using the elasticity curves.)

- **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No

f. **Scope: LDVs only, total transport, other sectors included** LDVs only

g. **Geographic scope: regional, national, international** California and other States with ZEV mandates

h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Natural gas and electricity; electricity sources come into the analysis only in considering greenhouse gas emissions

i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** None

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** As noted, scenario drivers are not clear, since paper does not describe how most listed government actions are taken into account in the analysis. Obvious drivers are initial hydrogen prices and vehicle prices, with progress ratios that drive down prices as production increases. Model clearly assumes that there are subgroups of potential vehicle purchasers who will pay a premium for a high technology, ultra clean vehicle.
4. **Identification of key roadblocks** No
5. **Interesting results/conclusions** Key conclusions are:
   a. "Relatively small investments now by government and industry can lower the price of both hydrogen and FCVs and pave the way for continued markets for FCVs free of any government subsidy." This investment will provide a small market for early adopters, gradually increasing market share and driving down prices.

   b. **Hydrogen in a FCV can compete with gasoline even with H2 from small scale reformers or electrolyzers.**

   c. Small scale hydrogen appliances can avoid the chicken and egg problem.

   d. Use of onboard fuel processors create multiple inefficiencies – weight addition, inability to reuse exhaust stream so loss of 10-20% of the H2 in the exhaust (though some can be used elsewhere), dilution of the input hydrogen stream yielding fuel cell performance loss (demanding a larger fuel cell for same output) and reduction in system efficiency. Methanol FCVs will get 28.6 to 37.9% less fuel economy than a pure hydrogen FCV; gasoline FCVs are down 36.7 to 55.8%.

   e. Hydrogen FCVs will get 3 times the fuel economy of a conventional ICE vehicle on the EPA test (I suspect this is quite a bit too high).

   f. Both the higher range and lower range pure hydrogen FCVs and the higher range methanol and gasoline FCVs yield over 20% internal rate of return on investment! The lower range gasoline FCV doesn't penetrate the market.

- **g.** Similarly, the hydrogen gas industry will make over 20% rate of return. Both conclusions depend on the government investing over $400 million in the initial 10 year period.
- **h.** Although small electrolyzers are crucial in supplying hydrogen to smaller stations, they will soon be superseded by steam methane reformers.
- **i.** In any case, electrolyzer use will dramatically increase greenhouse gas use given the U.S. marginal electricity mix. And renewable electricity would reduce greenhouse gases more by displacing fossil fuel electricity rather than making hydrogen.

6. **Comments on overall credibility (judgment by reviewer)**
    - a. The authors note that "the model outputs should be taken as a very broad, qualitative indication of what is possible in the long run…greatest value will be in comparing alternative transportation options, and in assessing the possible impacts of various government and industry actions." This is a useful warning, although even the comparative value of the outputs must be assessed carefully, since the high uncertainty associated with estimated costs and performance could easily skew the comparisons. However, there is strong value in applying a unified analysis to multiple options, with such parameters as discount rates and assumptions about technological progress being applied uniformly to all options.
    - b. Assessment of costs, although extremely uncertain, appears to be rigorous.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Owen, N. and Gordon, R., *"Carbon to Hydrogen Roadmaps for Passenger Cars: A Study for the Department for Transport and the Department of Trade and Industry*, Ricardo Consulting Engineers Ltd., RCEF.0124.31.9901, Client Confidential.
2. **Scenario description, if applicable**
   a. **Description of "vision," if applicable**: There are two vehicle scenarios
      - Low Carbon Route, with gradual electrification of vehicles leading to a full Prius-style diesel hybrid (basically heading towards fleet-wide penetration), ending with hydrogen fuel cell vehicles possibly with full hybrid plus fuel cell APU as an interim (bridge) vehicle (original list included a series hybrid, series hybrid with reversible fuel cell, and hydrogen ICE with reversible fuel cell, parallel hydrogen ICE hybrid, and parallel CNG hybrid with hydrogen APU – all unlikely to be practical)
      - Hydrogen Priority Route, moving from very mild hybrid (stop-start and regen) ICE vehicles directly to a very mild hybrid hydrogen ICE, adding 42V crankshaft-mounted electric machine, then adding a small hydrogen fuel cell APU and finally moving to a hydrogen fuel cell vehicle considerably earlier than the low carbon route.

      The scenarios do not consider infrastructure development or hydrogen production, although, in fuel cycle analyses, it is assumed that hydrogen will be obtained from natural gas for the period evaluated.

   b. **Dates and interval:**
      - **Low Carbon Route**

1.	Stop start vehicle	2004
2.	Stop start + regen braking	2007
3.	Stop start + regen + downsizing	2010
4.	Full parallel hybrid	2012
5.	Series hybrid (rejected)	2015
6.	Series hybrid + reversible fuel cell	2020
7.	Hydrogen ICE + reversible fuel cell	2025
8.	or Parallel hydrogen hybrid ICE	2020-2025
9.	or Parallel diesel hybrid + H2 APU	2020-2025
10.	or Parallel CNG hybrid + H2 APU	
11.	Fuel cell vehicle	2030

      - **Hydrogen Priority Route**

1.	Stop start vehicle	2004
2.	Stop start + regen braking	2007
3.	Hydrogen ICE with stop start + Regen	2008
4.	Hydrogen ICE Mild Hybrid	2010
5.	Hydrogen ICE Mild Hybrid + Small APU	2012

        6. Hydrogen ICE Parallel hybrid with 8 kW APU 2015
        7. Fuel cell vehicle 2020
    - **c. Extent of focus on transition; possibly break out 2010-2030?** This is all about the vehicle transition – trying to answer the question, "What is the best route for transitioning from a current conventional diesel vehicle to a hydrogen fuel cell vehicle?"
    - **d. Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Individual vehicle price, well-to-wheels CO2 emissions, vehicle weight
    - **e. Methodology: "eyeballing," stock model, historic analogy, etc.** Ricardo basically asks the following question: "Given a baseline vehicle powered by a modern turbocharged direct injection diesel, what technology route would be best followed to reach the final goal of a fuel cell vehicle?" Ricardo's approach is to evaluate, for two different scenarios, the costs, well-to-wheels CO2 outcomes, manufacturer and consumer risks and issues, and other factors (including whether or not the intermediate technology steps would make sense for the long-term if fuel cell vehicles ultimately were not successful). This is strictly an examination of technology introduction at the individual vehicle level. Careful evaluation of technology prices, technology impact on efficiency and well-to-wheel emissions; inclusion of costs and efficiency impact of emission controls to achieve existing and projected future emission standards. Minor attention paid to issues such as refueling.
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No
    - **f. Scope: LDVs only, total transport, other sectors included** LDVs only; primary analysis on a vehicle of the class of a Ford Focus, e.g. compact car, with simple assessment of applicability to other LDV classes
    - **g. Geographic scope: regional, national, international** not applicable
    - **h. Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** No evaluation of hydrogen production; natural gas reforming assumed as production technology for the purpose of well-to-wheels analysis
    - **i. Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** Very strong focus on economic/market pressures on the industry, and on customer preferences

3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Key drivers are said to be strong government incentives
4. **Identification of key roadblocks** Both technical and market-oriented:
    - a. Technical
        - Need to greatly improve efficiencies of all electric components

    - Requirement to greatly reduce cost, improve efficiency, reduce precious metal content of fuel cells
    - Problems with hydrogen ICEs -- NOx emissions, difficulty of obtaining adequate power density
    - Solid oxide fuel cell for APU has startup issues, crash safety issues
    - Need to resolve onboard hydrogen storage issues
    - Performance of fuel cell support systems – compressors, thermal, control, and electrical systems – are virtually never described by developers
    - Vehicle platform issues for interim hydrogen solutions such as use of hydrogen APUs with diesel powertrain.
    - Weight reduction technologies will be crucial in dealing with weight gains from added components in moving to greater electrification
    - The need for rapid infrastructure growth can conflict with safety issues, training issues – *note that much of the service and fueling infrastructure is outside of the direct control of the vehicle manufacturers*

  b. Market
    - Very high cost of introducing new products
    - Need to prepare the dealer/servicing network
    - Need to manufacture any new technology in significant volume in order to be cost-effective
    - Risk of a new technology attracting adverse publicity due to poor reliability or unexpected safety or environmental issues
    - Customer acceptance issues about acceleration feel of hybrids (susceptible to state of charge of the battery), engine shut-down during idle (and perhaps during deceleration and low speed driving), limited range
    - Resale values can be an important issue, given rapid technology changes, consumer acceptance risks for early models.

5. **Interesting results/conclusions**
  a. Starting from TDI diesel as a baseline, a move to a hydrogen ICE *reduces* efficiency because the hydrogen ICE is spark-ignited. European diesel perspective may be different from U.S. gasoline perspective.
  b. With natural gas-based hydrogen, mid-range efficiencies would allow a fuel cell to only match the well-to-wheels carbon efficiency of a diesel parallel hybrid. Even with the highest efficiency gains, the overall CO2 gain is not more than 10-20% until zero-carbon hydrogen is available.
  c. The Hydrogen Priority route is difficult because a number of the interim technologies are replaced soon after introduction, e.g. hydrogen ICE engine, fuel cell APU. However, moving directly to the fuel cell vehicle would yield very high cost initial vehicles with severe infrastructure issues, severe consumer issues.

   d. Important to consider alternatives to hydrogen, e.g. renewably synthesised liquid fuels.
   e. For the Low Carbon route, it is unlikely that any of the technology steps between step 4, the parallel hybrid, and the fuel cell vehicle will succeed because of their expense and lower efficiency without accompanying consumer benefits. However, the manufacturers may want to develop these steps in small quantities. The fuel cell APU is a possible exception, since it add to vehicle functionality….though with considerable cost and packaging challenges.
   f. **The incremental low carbon route is to be preferred over the hydrogen priority route, because the former is compatible with industry practices and the latter is not.** Radical technology change is viewed as harmful to the industry's financial viability and likely to be viewed by car-buyers as leading to reduced reliability, difficult maintenance, high depreciation, and high trade-in risk. The evolutionary steps to the fuel cell also represent CO2 benefits that would be lost if we had to wait for the full-fledged fuel cell vehicle without intermediate low-carbon technologies. And early fuel cell vehicles will be prohibitively expensive, especially if no intermediate technologies are allowed to develop and to reduce costs and increase performance over time. Progressive electrification offers more manageable risk coupled with significant CO2 benefits.
   g. Vehicles will have to meet progressively more stringent emission, safety, and consumer demands – trends in conventional vehicles show huge improvements in all of these factors, and such trends will continue…so advanced vehicles must anticipate having to meet substantially changed standards from those of today.
   h. Strong government promotion of advanced technologies is crucial to their development – R&D funding, vehicle purchase schemes, support of infrastructure development, and so forth
   i. Some technological bridges to fuel cell vehicles may represent a step backwards in cost and performance (for example, switching from a diesel engine to a hydrogen IC engine) yet play a valuable role in advancing infrastructure or other goals – which will require particularly strong government interference in the marketplace.

6. **Comments on overall credibility (judgment by reviewer) T**his analysis should be judged as extremely credible based on both the excellent reputation of Ricardo and the careful, dispassionate analysis. A key question must be, however, whether or not Ricardo is correct in assigning such a high priority to the need for an incremental approach to avoid market and technical risk. Also, Ricardo's analysis focuses almost exclusively on the vehicle; issues about hydrogen production and delivery infrastructure are obviously crucial to comprehensive scenario evaluation.

Hydrogen Scenarios Literature Review: R. Silberglitt and A. Hove, RAND Corporation, Scenario Analysis

This is a detailed examination of a large group of future energy scenarios from a wide variety of groups ranging from the Energy Information Administration and International Energy Agency to Royal Dutch Shell to a group of environmental organizations. The purpose is not directly related to hydrogen energy futures, and many of the scenarios do not project a major role for hydrogen – though many do. Also, the review does not focus on transitions and does not attempt to examine this issue in depth….but our previous examination of a range of scenarios found that virtually all of them did not address transition issues in any depth, and this appears to be the case with most of the scenarios examined in this review.

The review examines the following scenarios:

- Energy Information Administration: AEO 2000 with variants, two Kyoto Protocol analyses;
- Other econometric scenarios: IEA, GRI, AGA, IPAA, DRI, WEPA
- World Energy Council/International Institute for Applied Systems Analysis
- Royal Dutch Shell (Sustained Growth and Dematerialization)
- IPCC
- ACEEE, ASE, NRDC, UCS, Tellus (America's Energy Choices)
- Stockholm Environment Institute Global Scenario Group
- Inter-laboratory Working Group (Scenarios of U.S. Carbon Reductions, Scenarios for a Clean Energy Future)
- PCAST
- Romm, Rosenfeld, and Herrman (The Internet and Global Warming)
- Jesse Ausubel (Where is Energy Going?)
- Amory Lovins and Brett Williams (Strategy for the Hydrogen Transition)
- California Air Resources Board (Status and Prospects of Fuel Cells as Automotive Engines)
- A.D. Little (Distributed Generation: Understanding the Economics)
- Miscellaneous studies of specific energy resources, e.g. solar, geothermal

Key Conclusions/Observations

1. All of the scenarios fit into one of four clusters
    - Moderate growth-high environmental impact, basically extrapolation of current trends, though slight recarbonization with nuclear decreasing
    - Moderate growth-low environmental impact through improved technology
    - High growth-moderate environmental impact, basically business-as-usual growth but better technology
    - Low growth-benign environmental impact, environmentally conscious world, technology improvements, and change in lifestyle
2. One more scenario should be added: Low Energy Growth – Moderate Environmental Impact, either through economic downturn or supply

constraints or both, no new technology. This wasn't considered in the group of scenarios studied because all of them ignored surprises.

3. And this is a crucial conclusion: surprises, in the form of resource constraints, oil disruptions, or environmental surprise (large sign of global warming?) are not considered in any of the scenario analyses.
4. U.S. history is one of growth, crisis, adjustment, and more growth. At times energy growth has stopped (1974-1984).
5. The low growth-benign environmental impact scenarios demand that the U.S. do something it has never done before. Examples:
    - Decarbonization over last 40 years ~ 0.2%/yr; optimistic scenarios call for 1.6-2.6%/yr
    - Energy productivity (GDP/energy use) over past 40 years has increased by 1.8%/yr; pulling it down to 75-80 quads or so would require 3-5%/yr increase.
    - To analyze such a scenario properly demands explicit examination of rate of turnover of energy conversion and utilization equipment, time needed to implement lifestyle changes (work patterns, public transportation, land use).
6. Many scenarios suggest natural gas as a transition fuel, but there are real issues about natural gas supply that must be explored. Many scenarios assume U.S. production can be greatly increased (EIA Reference Case projects 9 additional quads by 2025 – a 40% increase) – seems debatable.
7. Also, many scenarios (esp. EIA) assume ready access to increased oil imports from Persian Gulf.

Hydrogen Scenarios Literature Review Bernow, S., "Challenges in Researching the Transition to a Hydrogen Economy," Nov 14, 2002 – key points:

1. Technology characterization: need scale dependence, technology learning function
2. Characterize existing hydrogen production facilities, potential for excess supply
3. Characterize existing feedstock potential, including electricity – including location
4. Characterize effect of electricity, natural gas use for hydrogen feedstocks on overall supply/price
5. Estimate potential demand for stationary hydrogen use, interaction with hydrogen availability for transportation
6. Develop scenarios for urban areas – specific cities or idealizations?
    - Resource constraints/endowments
    - Infrastructure needs and costs
7. Need cost curves/scale dependency of costs
8. Assessment of electric system impacts – analysis of true marginal electric sources, needed to identify carbon impacts

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable Bailie, A., et al, Tellus Institute, *Hydrogen Transitions in a Greenhouse Gas Constrained World, Volume I: Main Summary Report,* Draft, August 2005.**
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: two contrasting policy contexts – BAU and GHG-constrained" – with each having a hydrogen and non-hydrogen scenario; also, a BAU+year 2025 shock that demands rapid hydrogen deployment. Transition is driven initially by fleet use and limited introduction of dual-fueled ICEVs.
    b. **Dates and interval:** 2005-2050
    c. **Extent of focus on transition; possibly break out 2010-2030?** No specific breakout, but scenarios move from low demand and decentralized production to intensifying demand and centralized production, so transition is described; one figure gives delivered hydrogen costs in first 10 years of scenario
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Vehicle stock, crude oil demand, carbon emissions, delivered cost of hydrogen and individual cost factors, e.g. capital costs for facilities, etc. (not clear whether this is calculated outside or inside of model)
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Stock model is used, but details of other modeling and calculation unclear from report. Feedstock types apparently are assumed in model, based on external analysis considering resource availability. Key assumption is FCV sales, which apparently drives hydrogen demand
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No
    f. **Scope: LDVs only, total transport, other sectors included** Road transport plus cogeneration/combined heat and power.
    g. **Geographic scope: regional, national, international** National and four cities
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** multiple
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** inclusion of a "shock" scenario
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Analytically, scenario is driven by assumption of penetration of FCVs and dual-fuel ICEVs; but scenario logic is that extensive government incentives coupled with societal attitudes drives the scenarios.
4. **Identification of key roadblocks** Discussion primarily; analysis doesn't directly focus on roadblocks. R&D hurdles; existing infrastructure for gasoline; "chicken and egg;" competing solutions.

5. **Interesting results/conclusions**
   - **a.** Hydrogen remains considerably more costly than gasoline
   - **b.** FCV lifecycle costs don’t match CVs for lifetime of study
   - **c.** All of the long-term climate-friendly options are centralized options
   - **d.** Grid electricity will not allow climate-friendly hydrogen
   - **e.** In the near term, hydrogen development will have negative benefits
   - **f.** A credible hydrogen scenario will take as much as 50 years to unfold.
6. **Comments on overall credibility (judgment by reviewer)** We need access to the Volume II, the methodology report, to appropriately evaluate credibility.

Hydrogen Scenarios Literature Review: Andrews, C.J., and Weiner, S.A., "Visions of a Hydrogen Future," *IEEE Power & Energy Magazine*, March/April 2004.

This paper is a discussion of issues facing a hydrogen transition, e.g. the types of incentives that will be needed for a successful transition and other public policy issues such as the criteria for judging alternative pathways. Points in the paper applicable to transition modeling are:

1. "Policymakers must have insight into the external and internal issues and challenges faced by the organizations whose actions are intended to be motivated."
2. Both companies and localities may prefer to take the lead or else follow (and assume fewer risks), and incentives must be designed for each.
3. "State and local policies will strongly influence the development of a hydrogen economy, and State and local governments vary greatly in their preferences, capabilities, and circumstances. The seeds of the hydrogen transition will encounter more fertile soil in some jurisdictions than in others."
4. Reviewer's comment: The key here is that modelers will have to take account of local and State conditions and policies, and these will vary considerably from place to place….implying a real challenge to modeling the transition. Clearly, significant parametric analysis will be required, at a minimum.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** Tseng, P., Lee, J., and Friley, P., "A Hydrogen Economy: Opportunities and Challenges," *Energy*, not published at time of review.
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: Transition to hydrogen where low feedstock costs and low fuel cell system and hydrogen production costs allow hydrogen to compete with gasoline. For example, 2015 fuel cell vehicle incremental cost is 15%, or $3,000 for a $20,000 vehicle. Production cost of hydrogen is $0.50-$1.00/GGE at the gate, with moderate transportation costs.
    b. **Dates and interval:** 2000-2050, in 5 year increments
    c. **Extent of focus on transition; possibly break out 2010-2030?** Transition period is not explicitly singled out, but model should be able to handle transition issues. However, paper states that it "does not address the chicken-and-egg problem."
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Full range of variables, from gasoline price and consumption to hydrogen price to FCV penetration to carbon emissions.
    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** MARKAL model – dynamic linear programming model (finds a least-cost solution to meet user-specified energy service demands, e.g. vmt). "Special attention was paid to the expansion path of manufacturing capacity that produces hydrogen, fuel-cell vehicles, and infrastructure."
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** Yes, slate of production technologies includes a biorefinery capable of producing liquid fuels; vehicle technologies include hybrids and diesel hybrids.
    f. **Scope: LDVs only, total transport, other sectors included** MARKAL is economy-wide, so other sectors are represented; paper does not make it clear whether stationary hydrogen fuel cell use for electricity/heat/cooling is a factor.
    g. **Geographic scope: regional, national, international** National
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Coal, natural gas, biomass, electricity
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** Not apparent
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Paper seems to imply that the only driver is government R&D that helps drive costs down to competitive levels; no other policy measures are mentioned in the scenario description.
4. **Identification of key roadblocks** Potential roadblocks discussed include:

   a. Potential for technology lock-in if infrastructure is established to accommodate a particular technology, e.g. natural gas.
   b. Declining gasoline price caused by hydrogen penetration could slow market penetration of fuel cell vehicles. Significant alteration of refinery economics can cause problems with petroleum products. Oil producers could try to maintain market share by dropping prices to marginal cost of producing oil.

5. **Interesting results/conclusions**
   a. The market penetration of fuel cell vehicles – 50% of passenger travel by 2050 – coupled with improved efficiency in vehicles using liquid fuels -- moderately reduces primary energy use and substantially reduces oil use. In 2050, primary energy use is reduced by 7.5 EJ from the reference 173.6 EJ, or 4%. Oil use is reduced by 17 EJ in 2050, from a reference of about 70 EJ, or about 25%.
   b. The substantial reduction in gasoline use yields a decline in gasoline price of over 50% by 2030, as gasoline changes from a premium fuel to a joint product or byproduct. Prices for diesel fuel and petrochemical feedstocks rise as reduced refinery throughput reduces refining flexibility.
   c. Oil prices do not drop substantially from the reference case, because it is assumed that oil producers do not expand supply as rapidly as in the reference case. However, an alternative assumption could be that producers would try to maintain market share by keeping prices down closer to the marginal cost of production. This would yield sharply lower oil prices and a different equilibrium (lower hydrogen share) than if oil prices had remained high.
   d. With the higher price for petrochemical products, biorefineries capable of producing both such products and hydrogen might become attractive, depending on successful outcome of ongoing R&D for such plants. Similar opportunities may exist for coal and other renewable technologies.
   e. Also, petroleum refiners will have strong incentives to develop new refining technologies that allow production of substantially less gasoline while maintaining high production of other products.
   f. Policymakers might want to insure that gasoline prices will not drop as much as projected, to maintain national security objectives and to boost penetration of hydrogen vehicles.

6. **Comments on overall credibility (judgment by reviewer)**
   There are insufficient details in the paper to allow judgment about credibility. In particular, it is unclear how the transition to hydrogen occurs, and how the market barriers are overcome. Note that hydrogen system costs are *assumed* to be at levels that make hydrogen cost-effective.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable** California Environmental Protection Agency, *California Hydrogen Blueprint Plan, Volume 1 and 11, Draft Final Report,* March 2005; also, *Rollout Strategy Topic Team Report; California 2010 Hydrogen Highway Network,* January 5, 2005. Website: www.hydrogenhighway.ca.gov
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: Three-phase plan to introduce hydrogen to California highways, with the goal of making California "a world leader in hydrogen development and deployment," to improve California's energy security and environment and reap major benefits in economic growth:
        - Phase 1: 50-100 stations (from 39 current and planned) by 2010, serving primarily fleet vehicles (up to 2,000 LDVs, including some hydrogen ICE vehicles; 10 heavy-duty vehicles), with 5 "energy stations" – concentrated in urban areas, with a few on highways linking areas. These stations must have "anchors," that is, a baseload demand source – probably government fleets. Also, government sites should be looked to for stations, especially building on existing national gas refueling sites (though public access points must be carved out).
        - Phase 2: 250 stations, 10,000 LDVs, 100 heavy-duty vehicles, 60 stationary or off-road H2 applications, more energy stations, hydrogen home fueling stations; strategic stations linking urban areas
        - Phase 3: 20,000 LDVs, 300 heavy-duty vehicles, 400 stationary or off-road H2 applications, doubling of capacity utilization, expanded role for energy stations
        - In all phases, a mix of hydrogen-production technologies, adoption of a statewide uniform permitting process and regulatory approvals of hydrogen stations, 50/50 government cost share for stations, with $10,000/vehicle incentives for fuel cell vehicles during Phase 1

    b. **Dates and interval:** 2010 completion of Phase 1; Phase 2 and 3 timeframes are not specified

    c. **Extent of focus on transition; possibly break out 2010-2030?** Transition only

    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Fuel cycle **e**nergy and emissions on a "per vehicle" basis; total station costs, operating costs, and revenues

    e. **Methodology: "eyeballing," stock model, historic analogy, etc.** Engineering analysis without attempting to use formal modeling or even stock model – just focused on the transition without worrying about retiring and replacing vehicles.

        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No
    f. **Scope: LDVs only, total transport, other sectors included** Highway vehicles plus some stationary H2 use in multi-use refueling stations
    g. **Geographic scope: regional, national, international** California urban areas with highway networks interconnecting
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Multiple production technologies and feedstocks
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** No
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Basically full State government involvement in planning and financing vehicles and infrastructure: government fleets; government 50/50 cost share of stations, and $10,000/vehicle subsidy for fuel cell vehicles; development of codes and standards, and uniform station siting protocols; State education and publicity initiatives. Consideration of an array of measures, ranging from fuel subsidies to reduced vehicle registration fees to HOV lane access for H2 vehicles.
4. **Identification of key roadblocks** "Chicken and egg" problem (for which this scenario plan was designed to overcome); lack of codes and standards
5. **Interesting results/conclusions**
6. **Comments on overall credibility (judgment by reviewer)**

This is the most ambitious and thorough planning measure reviewed, with exceptional attention to station siting and other issues. However, it all depends on some very shaky foundations – huge declines in technology costs; public and company willingness to purchase vehicles with limited refueling options, potential resale problems, and highly uncertain maintenance costs; company willingness to invest in stations that might end up stranded, with a history of failure in methanol, for example; etc.

Hydrogen Scenarios Literature Review: Papers/Reports About Potential Roadblocks to a Hydrogen Economy

CERA, "The Hydrogen Economy: How Far and How Fast?, Cambridge Energy Research Associates, 2003, www.cera.com

1. Reviews the generally well-known issues with hydrogen, e.g. low energy density, energy requirements for production, distribution, and compression, on-board storage issues
2. Electrolysis issues: current 75% process efficiency; issue of competition from direct use of electricity in EVs (or plug-in hybrids?)
3. Compression energy ~ 50% of H2 energy content for 10,000 psi
4. Hydrogen is the most expensive of numerous options to remove CO2 from the economy

Bossel, U. and Baldur, E., "Energy and the Hydrogen Economy," January 8, 2003, http://www.idatech.com/technology/fuel_processors.html.

1. Basically this is an energy analysis of hydrogen, concluding that it is not practical as a fuel except for niche markets, and suggesting instead that we should turn to synthetic hydrocarbons based on renewable carbon sources.
2. Energy density: at 800 bar hydrogen, same density as liquid hydrogen; methanol is 1.8 times denser, gasoline is 3.4 times denser not counting storage tank differences
3. Compression energy ~ 7.2% of H2's HHV for 200 bar, ~13% for 800 bar, not including electrical losses (appears to contradict CERA's 50% estimate above, but perhaps that estimate includes electrical losses)
4. Liquefaction energy will not be much below 30% of HHV of the H2 for very large plants; and energy rises markedly for smaller plants
5. Storage in chemical hydrides is also very energy intensive: 59% of HHV for CaCO3, 76% for NaCl, 62% for LiCl
6. 22 tube-trailer hydrogen trucks or 4 liquid hydrogen trucks would be required to deliver the same amount of energy as one gasoline truck
7. Existing gas pipelines cannot be used for hydrogen because of diffusion losses, brittleness of materials and seals, incompatibility of pump lubrication with hydrogen, etc.
8. Long-distance pipeline shipments: 1.4% H2 consumed/150 km
9. Local electrolyzers: generation and compression to 200 bar; total energy = 150% of H2 HHV

Science, Toward A Hydrogen Economy, Vol 305, August 13, 2004.

1. News: The Hydrogen Backlash
   a. Current steam reformers are 85% efficient
   b. 10,000 psi tanks ~ 8 times gasoline storage volume for equivalent energy content

    c. Hydrogen tank truck going 500 km uses energy equivalent of 40% of its cargo
2. Turner, J.A., "Sustainable Hydrogen Production"
    a. Conversion of total U.S. LDV fleet ~ 100 billion gallons of water/year, vs. 4800 billion gallons/yr for domestic personal use, 300 billion gallons/yr for gasoline production

Wilson, J.R., "The Truth About Hydrogen, Version 4.0," TMG/The Management Group (www.tmgtech.com), September 25, 2003.

This is a detailed response to Amory Lovins' "Twenty Hydrogen Myths." Crucial points, especially with regard to modeling a transition, are as follows:

1. PEM cell efficiency is ~ 35-50% (30-40% at high load, 40-50% at low load), not the ~50-70% often claimed, when all accessory and parasitic losses are accounted for.
2. Reliability and durability of fuel cells, especially membranes, still requires major work. Unless this issue is laid to rest, it must be well accounted for in vehicle choice modeling.
3. Although load reduction is a key way to reduce the hydrogen storage problem, Lovins' suggestion of ultralightweight composite bodies ignores the many failed efforts at developing mass-manufacturable composite bodies.
4. Small-scale reformers and electrolyzers represent a major safety problem, especially given the likely problem of maintenance.
5. Hydrogen safety – although hydrogen does disperse rapidly, hydrogen flames are intensely hot, hydrogen is extremely flammable, and hydrogen flames and explosions can quickly involve other energy sources.
6. As with other critiques, great care must be used in doing a well-to-wheels analysis of hydrogen, particular with regard to compression and liquefaction energy costs, things like AC-to-DC power requirements, large transportation energy requirements, etc.

Hydrogen Scenarios Literature Review:

1. **Full citation, including web site if applicable:** ***Towards a European Hydrogen Energy Roadmap*, HyNet, May 12, 2004.**
2. **Scenario description, if applicable**
    a. **Description of "vision," if applicable**: Hydrogen buildup in portable fuel cell applications (important in getting the public comfortable with hydrogen, not important with regard to hydrogen supply), stationary applications beginning in 2006-2008 based on reformer-supplied hydrogen, with hydrogen delivery infrastructure developing after 2020), and transport beginning with fleets, moving to passenger cars around 2010-2015, with a mix of fuel cell and ICE hydrogen vehicles. Mid-range scenario of 50,000 cars by 2010, 530,000 by 2015, 5 million by 2020 (range: 2-9 million)
    b. **Dates and interval:** as above
    c. **Extent of focus on transition; possibly break out 2010-2030?** Primary focus is on transition, primary issues that will arise
    d. **Key variables projected, e.g. petroleum consumption, carbon equivalent, FCV penetration, hydrogen price** Focus of paper is on identifying transition issues rather than projecting impacts, so little attention to tracking variables – scenarios defined by number of vehicles and resulting hydrogen demand (e.g., 2-9 million hydrogen-fueled cars create demand for 0.2-1.8 million (metric) tons of hydrogen annually.
    e. **Methodology: "eyeballing," stock model, historic analogy, etc** Expert judgement; no indication that a stock model was used
        - **Does analysis/modeling include consideration of hydrogen's competitors, e.g. biomass to liquids?** No
    f. **Scope: LDVs only, total transport, other sectors included** As noted, multi-sector
    g. **Geographic scope: regional, national, international** European Union
    h. **Hydrogen production: feedstocks (biomass, wind electricity, etc), technologies** Wide range of production alternatives
    i. **Unique characteristics of the scenario development, e.g. risk analysis/scenario probability** None
3. **Identification of key scenario drivers: technology advances; government policy measures (subsidy/incentives; CAFE regulation; government fleets; demo projects; broken out by H2 specific and general); changes in consumer attitudes; high fuel prices** Key driver is government policy, including government procurement of fleet vehicles, with strong technology advances required, need for stakeholder partnerships; exploiting synergies among different end use sectors, e.g. hydrogen vehicles and windpower; special features of vehicle and stationary hydrogen use, e.g., for stationary, higher efficiency, reduction in noise, reduced maintenance, high availability, improved grid reliability and synergy with other energy end-use sectors.
4. **Identification of key roadblocks** Identification of roadblocks is a key output of this paper: risk of stranded investments; concerns about business case for

refueling stations (chicken and egg issue); need for advances in onboard hydrogen storage; costs of hydrogen transport and storage; lack of small reformers in the 1-10kW class (for stationary use).

5. **Interesting results/conclusions**
    - **a.** Transition phase fueling station infrastructure for 5,000-10,000 stations, supporting 2.0-4.4 million vehicles (5,000) to 5-9 million vehicles (10,000), 4-8% of European stations: 4-7 billion euros for 5,000, 7-15 billion euros for 10,000.
    - **b.** Very large risks in refueling investment, difficult balancing act between maximizing station usage with fewer stations and automakers' need for a fast vehicle ramp-up, which requires maximum consumer convenience.
    - **c.** Planners must assume that unforeseen barriers exist, so must maintain vigilance and be ready to react.
6. **Comments on overall credibility (judgment by reviewer)**
   Thoughtful evaluation and recognition of uncertainties and important barriers. Did not clearly recognize vehicle cost as a significant barrier, which it is.

Energy Systems Division
Argonne National Laboratory
955 L’Enfant Plaza SW, Suite 6000
Washington DC 20024-2112

www.anl.gov

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC