CONSULTANT STUDY REPORT

Bringing Fuel Cell Vehicles to Market:

Scenarios and Challenges with Fuel Alternatives

October 2001

Prepared for
California Fuel Cell Partnership

Prepared by
BEVILACQUA KNIGHT, INC.

with associated consultants

Bringing Fuel Cell Vehicles to Market:

Scenarios and Challenges with Fuel Alternatives

Consultant Study Report

October 2001

(Version 1.1)*

Prepared for

California Fuel Cell Partnership
3300 Industrial Boulevard, Suite 1000
West Sacramento, California 95691

By

BEVILACQUA KNIGHT, INC.

with associated consultants
3937 Trust Way
Hayward, California 94545

*Version 1.1: Minor text and graphics production edits February 2002 (no content changes)

Disclaimer

This report was prepared by an independent team of consultants led by Bevilacqua-Knight, Inc. under contract to the California Fuel Cell Partnership. All statements of fact, opinion, and assumptions contained in this report are attributable to the consultant team and do not necessarily represent the opinions or views of the California Fuel Cell Partnership or any of its members.

Ordering Information

Requests for copies of this report should be directed to the California Fuel Cell Partnership by e-mail to info@cafcp.org or phone (916) 371-2870.

Printed on recycled paper in the United States of America

Acknowledgements

This report for the California Fuel Cell Partnership is the product of a team of consultants retained by the CaFCP to identify challenges and solutions to the commercialization of fuel cell vehicles using several fuel alternatives. This study team includes a broad range of expertise, ranging from study design, technology commercialization, and the automotive market to specifics of fuel cell vehicle and infrastructure technologies, regulation, and impacts. The team worked to compare and reconcile their own perspectives as well as those of CaFCP members and other experts. Members of the study team included the following:

- Robert Knight, Bevilacqua-Knight, Inc., Hayward, CA (study design, issue definition and analysis, collaborative process, integration, reportage)
- Stefan Unnasch, Arthur D. Little Inc., Cupertino, CA (fuel economy, environmental impacts, economic modeling, regulation, and interpretive assistance)
- Ron Dickenson and other experts at SFA Pacific, Inc., Mountain View, CA (fuel sources, refining, reformers, costing, delivery and impacts)
- Barbara Richardson, University of Michigan Transportation Research Institute, Ann Arbor, MI (automotive industry, market research, consumer behavior)
- C. E. (Sandy) Thomas, Directed Technologies, Inc., Washington, D.C. (fuel economy and emissions, fuel processing, fuel cell technology, economics)

Several other specialists were particularly valuable advisers to the consultant team:

- Jim Crocco, Crocco & Associates, Plano, TX (methanol)
- Robert Reynolds, Downstream Alternatives, Inc., South Bend, IN (ethanol)
- Peter Schwartz, Global Business Network, Emeryville, CA (future scenarios)

Dr. Shannon Baxter of the California Air Resources Board was the CaFCP's Project Manager and deftly coordinated the involvement of its members, many of whom contributed valuable technical insights and reviews throughout the study. Catherine Lentz, Program Manager of the CaFCP, also offered key insights and wise guidance throughout. The U.S. Department of Energy's technical staff and consultants in the Advanced Vehicle Technology and Hydrogen programs provided briefings and access to current R&D information. However, the consultant team contractor is solely responsible for the report's structure, content, and conclusions.

Robert L. Knight, Ph.D.
Bevilacqua-Knight, Inc.
Consultant Team Director

Table of Contents

APPENDICES

Table of Exhibits

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Additional exhibits in appendices

1 Executive Summary

1.1. Overview of the Study

The study's overall goal was to identify challenges and solutions for four different fuel scenarios and to determine the actions necessary, with regard to both industry and government, to commercialize light-duty fuel cell vehicles (FCVs) in a near to mid-term timeframe. The study sponsor was the California Fuel Cell Partnership (referred to in this report as the CaFCP). At the CaFCP's request, the study focuses on relatively early commercialization levels and on the California market as the assumed point of initial commercial distribution, although broader and longer-term implications are also considered. There is no specific calendar target for this commercialization, although estimates of minimum possible times are derived for some key steps.

1.1.1. The CaFCP's Study Specifications

- Focus on early market introduction of light duty trucks and autos in California
- Separate studies of hydrogen, methanol, gasoline, and ethanol fuels
- Intent is to identify plausible scenarios for success of each fuel option, with specific challenges and solutions for each, rather than to predict outcomes or compare fuels
- Commercialization to be expeditious but no timetable specified or to be derived in the study
- Initial step: Hypothetical pre-commercialization "pilot phase" of approximately 1,000 vehicles
- Commercialization criterion: Annual sales growth milestone of 40,000 vehicles per year in California; also an accelerated alternate goal of 100,000 in same approximate time period.
- Assumption that all on-board vehicle technology will be available as needed

1.1.2. Important Limitations of the Study

- Geographical focus on California as world's assumed first FCV market (although implications of broader simultaneous introduction elsewhere were also considered)
- Early market only: Only to 40,000 (and 100,000) vehicles/year in California, i.e., 2-5% of new vehicle sales
- Restricted to identifying a plausible success scenario for each fuel, based on a shared set of assumptions, rather than comparative sensitivity studies to judge the robustness of each fuel alternative
- Limitation to non-vehicular elements of commercialization, excluding on-board technology and costs for the different fuels

1.2. Use of This Report

This study was intended to identify commercialization pathways, challenges, and solution strategies for each of the four FCV fuel alternatives, seeking common elements as well as unique challenges for each. This information is for use in a variety of ways:

- Structuring further **industry discussion** of issues
- Developing **marketing strategies** and programs
- Specifying initial FCV **product packages**
- Organizing and financing **infrastructure**
- Resolving **governmental oversight concerns** at all levels
- Developing long-term **business cases** for FCVs
- Evaluating **risks** of FCV commitments
- Integrating **public benefit and governmental support** for FCVs

1.3. The FCV Vision and Commercialization Pathways

1.3.1. A Vision of Fuel Cell Vehicles in Society

In this study the fuel cell vehicle is viewed as a potentially major source of societal benefit in addition to its advantages for users. In the long term, the FCV will be a key element of a sustainable global energy strategy. No matter what initial fuel source is used, ultimately the FCV's fuel flexibility will allow widespread displacement of combustion-engine vehicles of all types and a transition to renewable and nonpolluting resources to provide the hydrogen needed.

Those future energy resources may include combinations of technologies such as solar and wind-based electricity for electrolysis as well as biomass-derived liquid fuels. The FCV's energy supply needs will also help build demand and economic justification for those renewable energy technologies, accelerating their R&D support, success, and adoption for uses far beyond transportation.

Governmental assistance is likely to be needed to help overcome initial investment risks, and may be justified by long-term societal benefits. Some appropriate roles of government include support of R&D, initial demonstrations, and early deployment of FCVs and their new infrastructure requirements. While tax incentives, energy policies, and other government incentives can support those early market-opening efforts, it is assumed that FCVs will compete on their own merits in the long term.

1.3.2. The FCV Commercialization Scenario

To reach this study's near-term California FCV commercialization milestone of 2-5% of annual vehicle sales, the CaFCP specified a hypothetical pre-commercialization pilot phase of several years in which automakers would test, refine and demonstrate up to 1000 FCVs in public and private fleets. The study team anticipates that compressed hydrogen will be used in this phase, to allow an earlier start while on-board liquid fuel reformer development continues.

This pre-commercialization pilot phase is assumed to be followed by market introductions of FCVs first in California's three largest central metropolitan areas (the inner San Francisco Bay Area, the South Coast Air Basin, and the San Diego area), reaching the 2% (or 5% alternate) sales milestone within several years. Other geographic markets both in California and beyond would also open during this introductory period, with the timetable largely phased by infrastructure investment and construction limitations. Initial market growth and infrastructure development will be impeded by financial risk, possibly requiring governmental incentives to encourage the necessary investment and effort.

This initial market growth is envisioned to be supported by a minimum of 500 fueling stations in place by the time that early milestone is reached, balancing user convenience and infrastructure investment risk. The initial fuel source and pathway choice for commercialization will evolve through a combination of competitive fuel supply and conversion technology status, costs and returns, investment risk-taking propensities of the major automakers and fuel providers, and possibly governmental incentives at the time commitments will be required—2-3 years prior to market introduction. Both vehicle sales and fueling station construction will continue to expand rapidly thereafter as more and better FCV choices appear and fueling economics improve through increased volume. Meanwhile, the development of renewable energy sources will continue for all energy uses and move into use for FCVs as they become competitive.

1.4. Major Conclusions on FCV Challenges and Solutions

1.4.1. Fuel Reforming

Timely and effective fuel reforming technology development may be the most difficult challenge to early FCV commercialization. Many criteria must be met, from reliability, durability, and efficiency to feasibility of manufacture, safety, cost, and quality. To bring FCVs to market as early as possible, this challenge must be met successfully within the same timeframe as cost-effective fuel cells and related infrastructure.

This is especially so for the on-board reforming of liquid fuels considered in this study: gasoline, ethanol and methanol. Not all fuels are equally easily reformed, and their reformers are at varying stages of development. Competitive off-board reforming of natural gas and liquid-fuel hydrogen carriers also face substantial challenges. This technical topic was not included in this study. Instead, as directed by the CaFCP, the study's findings assume that the necessary reforming technologies for all fuels will be available and effective soon enough to merge with the other components of the FCV and infrastructure.

1.4.2. Success Scenarios

This study identified scenarios with key assumptions, challenges, solutions, and actions required for each FCV fuel option to succeed. For each fuel, this success was found to involve a variety of significant difficulties, possible delays, and risks. While this study's results must realistically assess the challenges to FCV commercialization, the study seeks to recommend what is required to accelerate fuel cell vehicle market introduction for each of the four fuel options with specific efforts and expenditures.

The study's focus on the early commercialization milestone of 40,000 vehicles/year in California helps to identify and focus attention on the key challenges and solutions for each fuel path, and so ultimately will help to achieve the earliest possible success. These findings are robust: Most of the challenges raised in this study will need to be met under any other FCV introduction scenarios, such as a longer transitional emphasis on the fleet market, more gradual mass market penetration, or a different initial geographic area.

1.4.3. Similarities and Differences In Commercialization Pathways Among Fuels

Some of the most difficult challenges to commercialization are common to all FCVs and require similar solutions. These key challenges include proving and building of consensus on the long-term societal value of FCVs, resolution of infrastructure costs, the development of practical fuel conversion and cleanup technologies, and the assembly of all the factors needed for successful market development. Proposed pathways to solution of each of these specific challenges are provided in this study.

Although some of the most critical challenges to commercialization are common to all FCV fuel types, there are also other major differences in barriers and solution pathways among the different fuel choices considered in this study. Specific technological needs and overall infrastructure cost differences create quite different business cases, leading in turn to differences in the levels and nature of governmental involvement that may be required to accelerate commercialization. Differences in apparent societal benefits among the FCV fuel types appear to parallel some of these differences in technological and cost obstacles—that is, higher benefits seem to go with higher costs and risks.

1.4.4. The Hydrogen Tradeoff

One major difference among fuels, as highlighted in this study, is seen in the early infrastructure cost. This study shows that this cost is much higher for gaseous hydrogen than for any of the liquid FCV fuels. While this difference is easily interpreted as a major disadvantage of the hydrogen alternative, a more realistic interpretation must include the offsetting costs of the on-board fuel reformers required by the liquid fuels as well as their developmental uncertainties. These reformer costs are also expected to differ among the liquid fuels. In addition, hydrogen may offer greater long-term societal benefits.

In effect, the hydrogen option moves the fuel processing off the vehicle and into the fueling station, thereby shifting but not eliminating the fuel processing costs: The hydrogen infrastructure costs more, but the hydrogen FCV is likely to cost less than its liquid-fueled FCV competitors. Which cost dominates? While beyond this study's scope and access to data, an analysis of comparative costs for this essential step may show hydrogen to be competitive with some of the liquid fuels. Collaborations between automakers and fuel providers may be required to properly treat those cost shifts.

1.4.5. Infrastructure Investment

Timely fuel supply and infrastructure are challenging for most fuels considered. Although there are many differences in the type and severity of difficulties facing each fuel option, all—with the possible exception of standard gasoline—will entail heavy costs, delayed returns on those investments, and major practical implementation challenges, particularly as the commercialization process broadens beyond initial introduction in California or elsewhere. This will require the beginning of discussions and negotiations, by or before the start of a pilot phase, among fuel providers, automakers, and public policymakers focused on selection of appropriate financing and risk management mechanisms from the broad range of models available for both the pilot phase and later full commercialization.

This study assumes that a key initial goal must be to keep the per-mile FCV fuel price at or below that of conventional gasoline during the market introduction period, with early financial deficits becoming gains as the number of FCVs grows and their fuel costs drop to viable levels. In addition, the study shows that the business cases for most fuels involve long periods of negative cash flow for fuel suppliers. This finding suggests that fuel suppliers are likely to require some form of investment risk management.

1.4.6. The Infrastructure Business Cases

The viability of the fuel infrastructure business case for each FCV fuel option is highly dependent on the economic assumptions used. This study adopted a limited "success" criterion of positive annual infrastructure cash flow within ten years of FCV market introduction. Cost modeling was used to identify a set of plausible values of key variables, including common as well as fuel-specific ones (e.g., California terminal price for methanol), that would yield such a result. The values used for the common elements of the commercialization scenarios were the same for the analysis of each fuel option. Examples include interest and capital recovery rates as well as time-varying assumptions such as the numbers of vehicles, fuel usage, and fueling facilities. Among fuel-specific variables, fuel tax rates were allowed to vary among fuels according to present practice and fuel costs were adjusted within plausible ranges to meet the model output criterion. As a result, these business case results should not be compared among the fuels. Their purpose is to identify illustrative multivariate scenarios under which each fuel could meet the success criterion, not to rate or rank fuel options.

An important finding is that the business cases are all <u>extremely sensitive</u> to their input assumptions, such as fuel feedstock prices, fuel tax policy, vehicle sales growth, infrastructure expansion strategy and costs, and the cost of capital. All the cases also assume no future stranding of their investments by later superior technology developments. Each business case can be either worse or better if reality proves to be different from those assumptions. While this study used assumptions judged by its authors to be plausible, these are not forecasts or expectations but illustrative values that combine to create a result that meets the success criterion. Users of this report are encouraged to alter those assumptions to meet their own expectations and requirements.

It is important to recognize that the methodology employed in this study is very different from one which projects the most likely values of the key economic variables and produces an estimate of the expected business case. Although prediction of the most likely values of the economic variables was outside the scope of this study, such projections will be an essential part of future work aimed at analyzing alternative business cases. A broad range of such future analyses will be needed, including input-sensitivity tests beyond those included in this study, worst-case scenarios, and others involving not only different inputs but other financial models or broader measures of success such as reductions in environmental protection costs.

1.4.7. Potential Roles for Government

Federal and state governments can play a decisive role in investment risk management. Because of the extreme sensitivity of the business cases—which in turn is caused by the volatility of key parameters when looking a decade or more into the future—risks of major financial losses are clearly present. It is understandable that major gasoline retailing companies may be hesitant to support FCV fuel choices that require heavy new investment in supply chain infrastructure. It will be difficult for any participant to justify the dedication of the large infrastructure investments, staff resources, and executive priority that will be required, unless steps can be taken to effectively reduce those risks.

R&D support is a governmental role already in place for FCVs, although expansion of that function could be considered. But the long-term public benefits of FCVs and their fuel alternatives are still unclear, and may prove to be large in comparison to the infrastructure costs and risks. Based on long-term public interest, both state and federal governments may also find other valuable roles in helping to manage investor risk through mechanisms such as investment tax credits, risk insurance, and direct underwriting of specific early expenses. In the longer term, however, FCV technology and economics must mature to full competitive ability in the marketplace.

1.4.8. Importance of Cooperative Effort

An unprecedented public-private cooperative effort will be necessary. Automakers, fuel providers, and government at all levels must cooperate to develop an adequate public market demand for FCVs, including the following steps:

…*Intensive and coordinated consumer education* must begin early, focusing on proving the capabilities, benefits, reliability, and affordability of fuel cell technology for both vehicular and stationary uses.

…*A broad early FCV product line* must be offered in order to capture buyers in a variety of market segments, or not enough vehicles will be sold to meet sales and profit targets

…*A portfolio of price incentives* will be required to offset the expected early vehicle and fuel cost premiums, both for consumers and providers. Users must be assured of reasonable continuity of such incentives with clear and fair sunset provisions.

…*A package of substantial non-price incentives* to the consumer will also be needed to overcome initial market resistance to the uncertainties of a new technology.

1.4.9. Societal Benefit Differences Among Fuels

The environmental, energy security and diversity, and public health and safety effects of different FCV fuels vary widely. These effects range from similar to those of projected hybrid ICE/battery vehicles to much better, depending on the fuel pathway chosen. This results in the possibility of different levels of public policy support and financing assistance among the candidate fuels. Immediate study is needed to refine and confirm the existing forecasts of such effects for each fuel, paralleled by policy analyses of their implications for societal value and levels of justifiable public support. Emphasis of such studies and policy development must be on <u>long-term</u> technological possibilities and their societal value rather than short-term benefits.

1.4.10. The Pilot Phase

An early pilot phase of FCV introduction could help in FCV market development, but should be focused primarily on fleets. The CaFCP specified that this study assume a 1000-vehicle pilot phase involving several automakers. The study's market analysis (see next section) suggests a need for a period of intensive and positive public exposure and education prior to full-scale FCV market introduction. In addition, automakers may favor such a trial period as a means of assuring the adequacy of FCV technology. Potential fuel providers facing major infrastructure investment for FCVs would be encouraged by such a display of automaker commitment, as well as given time for their planning, financing, and construction efforts in preparation for mass market introduction.

For these technical assurance and public education purposes, fleets of various types offer major advantages of infrastructure savings, performance monitoring, coordinated public education, and technology refinement. Limited participation of motivated early-adopter individuals is also possible for diversity of use. Efforts must begin at least two years in advance to prepare for that pilot test phase, including developing cooperative agreements among automakers, identifying appropriate individual fleets and their concentrations in specific areas in cities, negotiating fleet and fuel provider participation, including fuel price support mechanisms, and working toward needed local code changes and education of local permitting officials.

1.4.11. Market Development Challenges

The study's interim milestone sales rate of 40,000 vehicles/year in California will be very difficult to reach until several distinct vehicle choices are offered. The 40,000 vehicles/year sales milestone constitutes about 2% of forecasted annual deliveries of new autos and light-duty trucks in California, or about 3% of those sold in the state's three central urban markets: the inner San Francisco Bay Area, the South Coast Air Basin, and the San Diego area. Focusing initial FCV sales in those areas dramatically reduces the number of refueling stations needed initially, yet reaches the majority of the state's population. Placements of FCVs in fleets should also continue from the pilot phase. However, the alternative strategy of focusing initial FCV market introduction primarily on the fleet market only slows California sales growth due to the limited size and diversity of the fleet market.

The varying needs and desires of consumers have resulted in many distinct vehicle categories based on variables such as price range and vehicle type, e.g., a four-door sedan in the $30,000 price range. Despite this extreme market segmentation, the history of automotive innovation suggests that only one or two automakers may enter the FCV market within the first year, and with only a single model, while others may follow only after another year or two. Many potential early FCV adopters will thus have few if any FCV choices, versus many more conventional and hybrid vehicle alternatives that fit their needs. Unless FCV sales growth to the 40,000 level and beyond is to be delayed for lack of consumer choice, early sales or leases must be extremely strong or even dominant within their limited market segments. To reach a nominal 3% overall market penetration, the earliest FCVs available will need to be virtually irresistible within their limited markets. This is unprecedented, and will require a uniquely convincing package of vehicle features and support services plus unusually intensive marketing to differentiate the FCV.

1.4.12. Longer-Term Commercialization Challenges

After the first few years of market introduction, when the FCV population is growing fast, the rate of infrastructure construction may become a limiting factor. This study's focus was on the initial transition from FCV introduction to an interim mass-market penetration milestone (defined by the CaFCP as 40,000 vehicles per year in California sales). During those earliest years, the rate of fueling station construction is driven mainly by the need to establish minimal geographic coverage rather than adequate fueling capacity. However, the study's financial modeling results demonstrate that within the following few years, when the FCV population could be growing at a very high rate—e.g., 80,000 or more per year in California alone—it may become very challenging to meet the fast-growing demand for fueling capacity.

The illustrative market development assumptions used in this study for those later years resulted in a very high rate of fueling activity per dispenser (well beyond conventional practice) despite an increasing rate of construction and an improving financial case. Although such "problems of success" are beyond this introductory study's scope, we note that this topic requires further analysis and scenario planning. For example, more dispensers might be added more quickly at existing stations, while reducing the rate of new station development—reducing both cost and construction effort while providing more dispensers.

1.5. Major Fuel-Specific Conclusions

1.5.1. Hydrogen

- Low cost, highly integrated packaged fuel processing & vending apparatus is essential and needs extensive development
- The high hydrogen infrastructure costs and risks need to be addressed in negotiations among automakers, fuel providers, and government
- Strategic public education campaign is needed well before market entry to clarify hydrogen safety and convenience
- The "energy station" concept for integration of vehicle fueling, stationary power and heat, and renewable resource use should be developed quickly

1.5.2. Gasoline and Naphtha

- For gasoline, whether conventional or low-sulfur, the key infrastructure issue is avoidance of sulfur contamination of the fuel cell
- There are virtually no other concerns except for the gasoline reformer challenge
- Naphtha (or another FCV-specific refinery fuel), shares the sulfur and reformer concerns, but may offer a near-ZEV emissions classification benefit

1.5.3. Methanol

- Acute toxicity of methanol in human contact will require a variety of mitigations as well as strenuous public education
- The methanol reformer's early success is crucial, both in performance and cost

1.5.4. Ethanol

- Ethanol cannot be a stand-alone fuel for FCVs, due both to availability and price, and must be paired with naphtha or gasoline as a low-volume hedge against gasoline price excursions
- More study is needed of in-state production possibilities and feasibility

1.6. The Accelerated Alternative FCV Sales Milestone

An alternate 100,000 vehicles/year milestone can be reached in the same time only through acceleration of market entry and production by all automakers. With such a challenge to reach the 40,000 annual sales milestone quickly, the more aggressive 100,000-vehicle alternative can be reached only through combinations of three factors:

- An aggressive earlier first-entrant FCV introduction, to provide more time for market momentum to develop
- More automakers are encouraged to enter the market, and scale up production quickly—via competitive forces, technology advances, and/or incentives
- Automakers expand their initial FCV product offerings quickly to provide at least three times as many models (covering a broader range of market segments), compared to the few FCV choices in the 40,000 vehicle scenario

No major acceleration of infrastructure investment is required, since initial FCV sales in California would most logically still be concentrated in the dense urban areas where minimum acceptable access to fueling stations is already assumed. However, several automakers would have to greatly advance their production plans in order to provide the necessary range of vehicle choices to reach an adequate market. To achieve this higher level of early automaker commitment, one key action needed is the early and unequivocal demonstration of strong and effective governmental support, particularly in investment risk management. Another essential factor is the success of FCV developments and the pilot phase of market introduction, in technical performance as well as in media support and public interest.

Yet another powerful but unpredictable contributor to increased commitment to early FCV commercialization is a possible change in external conditions within the coming decade. The most effective external force would be expansion of public financial incentives and other policies favoring production of FCVs. Examples of motivators for such policy shifts include events such as the following:

- unsettling environmental changes such as visible global warming effects requiring major reductions in carbon emissions;
- major new world political tensions or threats based on growing competition for remote oil and gas; and
- unexpectedly large increases in fuel cost leading to new fuel economy interest by vehicle users.

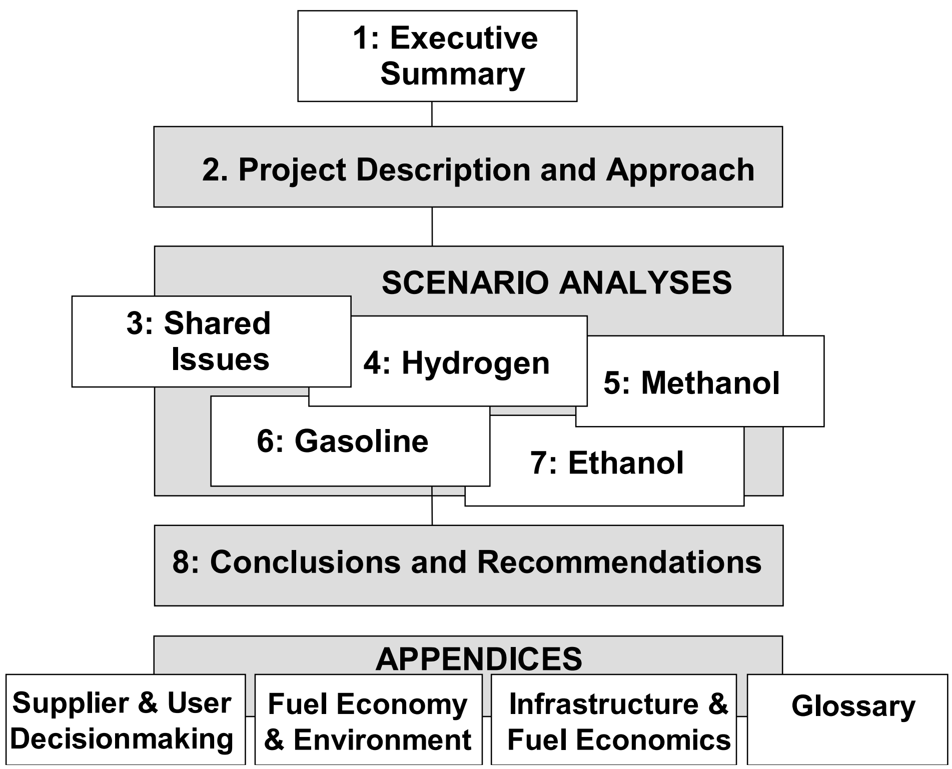
* * *

2 Study Description and Approach

2.1. Introduction to this Report

This report presents an integrated analysis of a broad range of requirements for early fuel cell vehicle commercialization. Exhibit 2-1 indicates the report's structure to allow the reader to find specific topics and levels of detail for examination.

Exhibit 2-1: Report Organization



- **Chapter 1** is a summary of the study's purposes, approach, findings, and recommendations.
- **Chapter 2** describes the study's purposes and approach, and derives an expected scenario for FCV commercialization.
- **Chapter 3** presents analyses of commercialization issues and challenges common to all FCV fuel options.
- **Chapters 4 through 7** report on the study's assessments of the commercialization challenges and solutions specific to each fuel option.
- **Chapter 8** presents the study's main conclusions and outlines the key activities to implement each fuel-specific scenario.
- **Several appendices** provide many additional details on specific topics.

2.2. The Study Approach

This study first describes a vision of a societally desirable future for FCVs, demonstrating a rationale for their commercialization. To create pathways toward that vision, commercialization scenarios and variations are developed for each of the four fuel alternatives. The broadest possible array of potential challenges to successful and expeditious market introduction are identified and organized into logical groups. The study's principal efforts are then focused on assessing those potential challenges to successful commercialization and developing ways of meeting them effectively. This process is applied separately but in parallel to each alternative fuel.

Those assessments of specific potential challenges, which form the bulk of this report, include both qualitative logic and judgment as well as quantitative studies where feasible and necessary. Best-available data and information are used, and uncertainties arising from lack of reliable predictive data are met through explicit assumptions and sensitivity analyses to permit alternative interpretations by users of the report. The result is a more focused set of challenges which appear most in need of early solution efforts beyond those already in progress, along with suggested specific solutions and comprehensive commercialization strategies.

2.3. The Fuel Cell Vehicle Vision and Pathway

2.3.1. Many Questions

Why fuel cell vehicles? Will there be clear advantages to the user, the maker, and the society? Will they be worth the heavy investments needed for their development and the new infrastructure that they may require? Can their advantages justify government incentives and other public policy changes that may be needed to introduce them into the market? These are questions frequently voiced as the auto and fuels industries confront the difficulties of such a major change in the way vehicles are built, powered, and fueled.

The CaFCP members and many others hold a vision of the long-term future that reaps major benefits of fuel cell vehicles for society and the environment as well as for their makers and users. The following paragraphs describe that vision.

2.3.2. A Long-Term Vision

Widespread use of mature fuel cell vehicle technology is still years—possibly decades—away. The full societal benefits of FCV technology may not be realized until even later. Although confidence in that long-term value requires further study, the potential benefits are many:

- Reductions in local air pollution, groundwater contamination, and greenhouse gases;
- Improved public health and safety from reduced exposure to fuel and emissions dangers;
- Reduced vehicular urban noise levels and associated stress;
- Increased national energy security, and with some fuels, diversity;
- Possible personal gains in vehicle-related cost savings and convenience; and
- Support and acceleration of the long-term trend toward a clean hydrogen and electricity-based economy.

These are benefits that would be valuable today, and may be essential in the decades to come. Even with the present uncertainties regarding the timing and extent to which FCVs can provide such benefits, and the differences in benefits among the different fuel pathways, the FCV's potential value is both so rare and so large that it must be a part of any vision of a desired global future.

2.3.3. Near-Term FCV Effects

The production and use of any of the potential *near-term* FCV fuel alternatives (including gasoline or related refinery products, methanol, ethanol, and compressed hydrogen from either electrolyzers or reformers using natural gas or liquids such as methanol) will not yield major reductions in air pollutants and GHGs compared to the best conventional and hybrid-powered cars and trucks, due both to the limitations of early fuel conversion technologies and the low numbers of FCVs involved. But the use of these fuels will be essential to introducing fuel cell vehicles as early as possible—thereby allowing the public the maximum possible time to gain familiarity with FCVs and move toward their widespread adoption. In this way the fuel cell vehicle market can develop in parallel with the necessary refinement in renewable energy technologies. The eventual merger of these two parallel paths will result in a true hydrogen-based mass market vehicle type with broad and stable market acceptance.

2.3.4. The Near-Term Fuel Choice

The California Fuel Cell Partnership is fuel-neutral for the introduction and commercialization of FCVs. There will be continued progress in a variety of FCV fuel processing, delivery, and storage technologies, and no "winner" is obvious. Accordingly, the CaFCP directed that this study seek to illuminate the paths toward each choice rather than selecting a preferred candidate. The initial fuel choice will be primarily a market decision based on technical feasibility, cost, consumer acceptance, and the business strategies of participants, including the assessment and acceptance of the technical and investment risks inherent in such a major innovation. It is possible that more than one early FCV fuel will be introduced during the first decade of sales, either in direct competition (e.g., in California) or in different areas of the world, although market actors may elect to move toward collaboration and avoid such risks.

2.3.5. The Renewable Fuel Vision and Investment Security

The initial fuel choices and investments will gradually build an early infrastructure that will carry risks of obsolescence by later transition to renewable fuels before full cost recovery. However, gradual evolution of the initial infrastructure is a more likely result. Although renewable energy sources such as wind power and biofuels may be a part of the initial infrastructure, the dominance of "ultimate" renewable hydrogen or hydrogen carrier sources for FCVs will emerge only gradually over several decades. Prior to any such long-term shift to renewables, as non-renewable hydrogen generation and on-board storage costs decline via continued innovation, the transition could begin. For example, hydrogen might be generated off-board from the initial fuel source and stored on-board as a hydride, while the earlier FCVs would continue to use the original fueling method. This would permit an orderly transition of the initial vehicle technology and fuel infrastructure, whether liquid or hydrogen-based. Thus the initial FCV fuel choices and their production methods, with some modification over time, could remain productive assets for their investors and the nation for several decades.

2.3.6. The Role of Government

Certainly fuel cell vehicle technology, including both vehicles and infrastructure, must be economically competitive in the long term. However, to move FCV commercialization ahead rapidly and yet yield acceptable investment risks, some significant interim governmental support may be required to overcome challenges to early FCV infrastructure development. The nature and scale of such support will ultimately be assessed and decided through the political process. The study provides some early infrastructure cost and business case estimates to help inform the public policy debate that is needed soon on this issue.

Since early FCV benefits will be small, due both to the small initial numbers of vehicles and the limitations of the initial technologies, government support must be based on a long view. Such a view may well be justified by the potential future societal benefits and the likelihood of delayed or failed FCV commercialization in the absence of such support. However, the study team concluded that the vision of a future with timely and important FCV impacts on air quality, global warming, and national energy security will require early, unequivocal, and effective government encouragement of this technology's development and commercialization—as well as similar encouragement of the renewable energy sources upon which its ultimate success will depend.

2.4. Project Specifications and Limitations

2.4.1. Project Specifications and Goals

The study's overall purpose was to identify challenges and solutions for four different fuel scenarios and determine the actions necessary, with regard to government and industry, to commercialize light-duty FCVs in a near to mid-term timeframe.

The California Fuel Cell Partnership directed that this study focus specifically on identifying the strategies, actions and resources required to successfully commercialize light-duty mass-produced fuel cell vehicles (FCVs) under each of four fuel options. The CaFCP's study specifications were detailed, and include the following requirements and assumptions:

- Initial market introduction assumed to be in California, extending shortly afterward to other unspecified regions internationally.
- Expedited efforts by all participants, but no rigid commercialization timetable specified or to be derived since the actual pace of development will evolve based on many factors—notably the commitment of all involved.
- First-stage goal: A pilot demonstration phase of approximately 1,000 vehicles.
- Commercialization-stage goals: Achievement of an annual sales milestone of 40,000 vehicles per year (and increasing) in California sales, with a secondary accelerated goal of 100,000 vehicles in the same time period.
- Four independent scenarios, each assuming use of only one of the following on-board fuel storage choices: hydrogen, methanol, gasoline, and ethanol.
- Inclusion of commercialization requirements common to all FCVs, irrespective of fuel choice, including factors such as market development strategies and the deployment of all infrastructure.

- Exclusion of the vehicle's on-board technical readiness and cost, including its fuel cell-related technology; CaFCP stipulated that the study assume auto manufacturers will be able to provide market-ready and cost-competitive vehicles by the time that all other challenges to commercialization are met.

2.4.2. Alternative FCV Fuels and Choices

This report does not offer direct comparisons or recommendations among the FCV fuel choices. The market's fuel choice will evolve gradually, based on many factors, as the alternatives are further developed. This study's purpose was to help identify the actions needed for effective commercialization of a range of candidate fuels, no matter which may be chosen for FCVs either initially or in the long term.

Readers are cautioned in using this report to compare and judge the relative merits of each fuel. Unintended biases can easily arise due to the study specification's explicit exclusion of the on-board elements of FCV technology. For example, the study's findings on compressed hydrogen's relatively high early infrastructure costs must be interpreted in comparison with the costs, technical problems, and uncertain timing of on-board reformers for the liquid fuel options—which, based on the study team's discussions with a variety of industry sources, are expected to vary widely among those liquid fuels—although vehicle reformer technology issues such as development timing and cost-reduction trajectory are not included in this study. The higher infrastructure costs for the hydrogen alternative may or may not prove to be similar to the total costs of liquid fuel reformers on every FCV.

2.5. Topical Scope and Structure

Exhibit 2-2 on the following page presents a simplified overview of the scope of this study. The major topics contributing to commercialization are listed as the rows in this table, ranging from environmental impacts to the decisionmaking requirements of the automakers. The range of these major topics is indicated in the left column, while the middle column highlight more specific challenges corresponding to each topic. At the right are examples of the kinds of activities needed within each topic to meet those challenges and move toward successful FCV commercialization.

Exhibit 2-3 expands on the broad picture presented in Exhibit 2-2 by presenting for each topic a more detailed listing of activities needed. The rows of the Exhibit 2-3 matrix represent a set of major topics or concerns that each fuel-specific study must cover, while the columns identify a set of principal functions in a comprehensive FCV "support system" that must be created and operated effectively for commercialization to occur.

The table entries indicate the spectrum of specific activities needed, and are the items assessed in the remainder of this study report.

Exhibit 2-2: Topical Scope

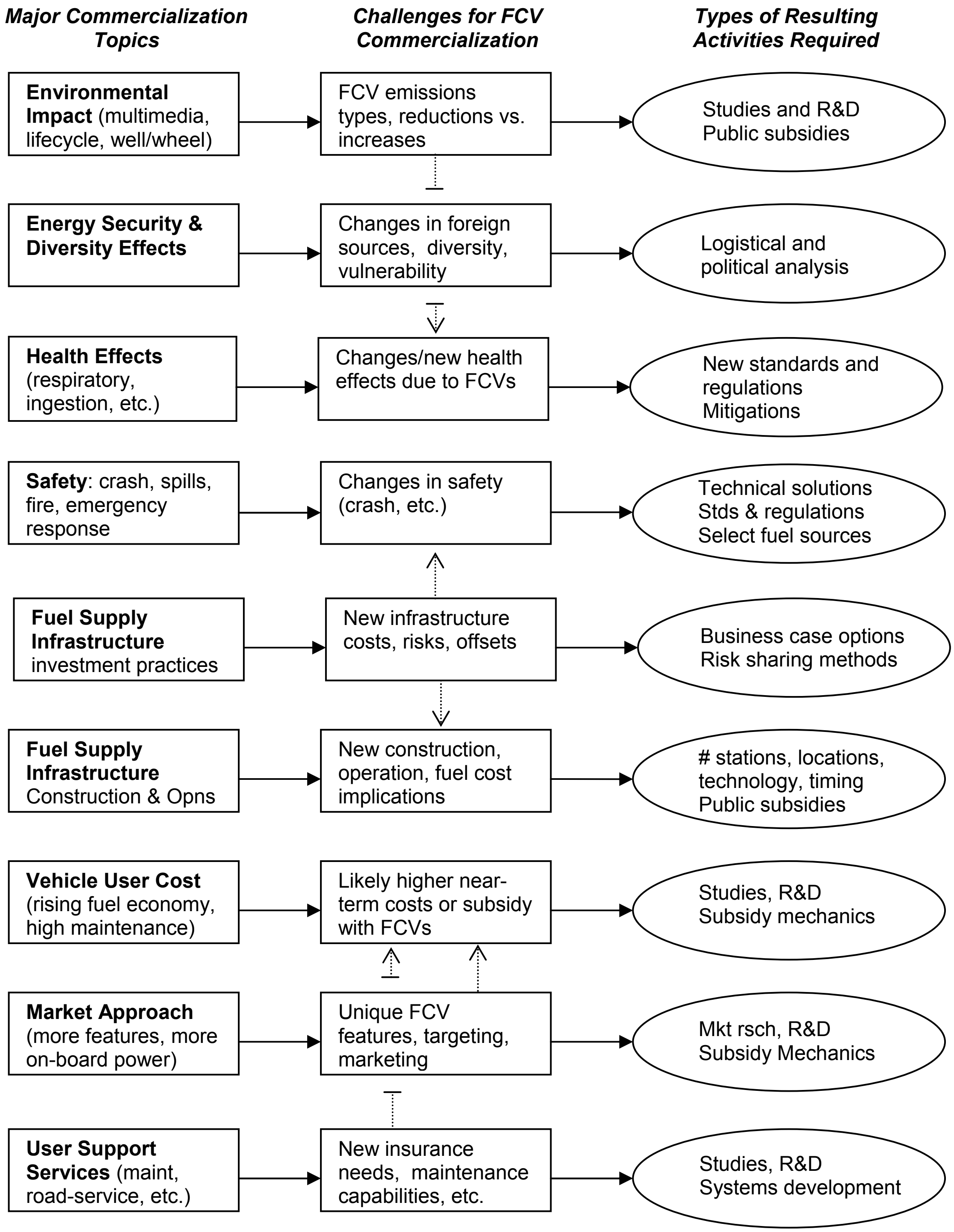


Exhibit 2-3: Commercialization Activities by Function and Topic

<table>
<tr><th>Functions & Topics</th><th>Procure, Treat, & Transport Fuel</th><th>Convert Fuel, Store, & Vend</th><th>Buy/lease, Use, Maintain Vehicle</th><th>Vehicle Life-cycle Support</th></tr>
<tr><td>Environmental Impact</td><td colspan="3">Identify/avoid/mitigate fuel spill danger →codes/stds
Assess related emissions & avoidance opportunities
Assure fuel resource availability</td><td>Assure reuse of scarce materials
Identify/mitigate fuel spill dangers →codes/stds</td></tr>
<tr><td>Health, Safety & Security Effects</td><td colspan="4">Develop safeguards for fuel ingestion avoidance & response→codes/stds/solutions
Develop safeguards for leak & crash-related ignition hazards→codes/stds/solutions
Create adequate emergency response systems→codes/standards/solutions
Reduce reliance on energy imports
Assure garage & shop safety→codes/standards/solutions</td></tr>
<tr><td>Infrastructure Construction, Operation, & Costs</td><td>Estimate investment
Estimate unit cost increment
Assess & include effects of competition & availability</td><td>Develop long-term fueling technology for economy
Estimate scale of Investment & govt support need
Estimate fuel price trajectory</td><td>Assure user's costs are acceptable: vehicle, fuel, maint., insurance
Identify and secure adequate govt. assistance based on public good</td><td>Develop emergency response systems & estimate costs
Support for insurance industry risk assessments
Establish vehicle service & repair</td></tr>
<tr><td>Infrastructure Investment, Risk/Return, Financing & Incentives</td><td></td><td>Assess costs/risks & demonstrate business case
Develop fuel provider alliances
Educate public officials & help create regulatory actions/incentives</td><td>Educate public officials & help create $$ govt. aid for early fuel price support
Same for seller incentives, as needed</td><td>Arrange emergency response systems financing</td></tr>
<tr><td>Vehicle User Cost (by time period)</td><td>Forecast increment of fuel cost</td><td>Forecast increment of fuel cost</td><td>Forecast trends in fuel cost, vehicle price, terms
Short-term vs. long-term business case</td><td>Forecast costs of maintenance, insurance, road service, resale loss</td></tr>
<tr><td>Market Approach: Initial Period</td><td>Identify and establish interim fuel sources and delivery</td><td>Identify most practical fueling technologies
Plan/provide limited infrastructure</td><td>Educate local officials
Identify & convince target fleets or other users to join</td><td>Provide high level of repair service
Provide FCV insurance</td></tr>
<tr><td>Market Approach: Longer-Term</td><td>Identify and establish longer-term fuel sources and delivery methods</td><td>Establish needed # & dispersion of public stations
Assure ease of use
Set acceptable fuel price and subsidy needs</td><td>Pick target users & continued fleet role
Educate consumers & local officials; monitor attitude
Demonstrate FCV econ/value/safety
Identify/provide user inducements</td><td>Provide high level of repair service
Assure low-cost insurance availability</td></tr>
</table>

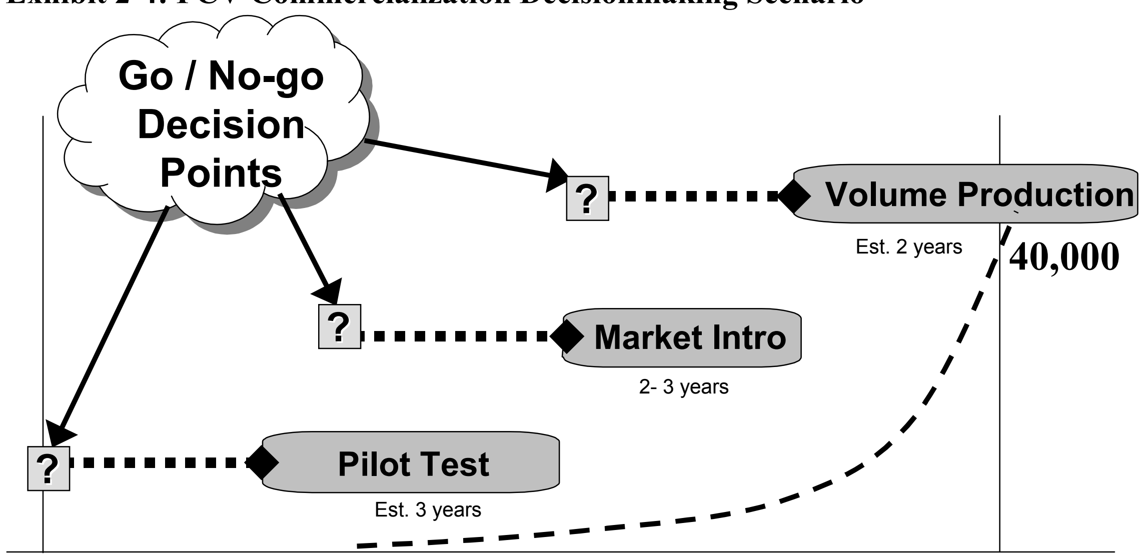
2.6. The Basic FCV Introduction Scenario and Decisions

Commercialization of any innovation occurs through a series of strategic investment actions, or decisions, by the backers of the innovation. These decisions may range from R&D funding through market development, production engineering, initial production capabilities and operations, and strategic expansions. Each of these strategic decisions is influenced by a variety of factors such as technical accomplishments, capital funding availability, public incentive policies, and competition.[1] Following this model, achievement of either the 40,000 California vehicles/year milestone or the 100,000 vehicles/year alternative are assumed to be based on a necessary sequence of three key FCV investment decisions by automakers and fuel providers:

- Pilot phase FCV production and deployment
- Series-scale commercialization and fueling infrastructure
- Large-scale mass production and fueling infrastructure

The resulting commercialization scenario is shown in Exhibit 2-4. The decisions and their rationale are described in the following paragraphs.

Exhibit 2-4: FCV Commercialization Decisionmaking Scenario



---

[1] Stationary fuel cells may be introduced and sold in substantial volumes for a variety of uses well before FCV market introduction. Such innovation could help to assure and accelerate FCV commercialization through R&D advances, cost reductions, buyer familiarization, and associated declines in FCV developmental risk. This would make the key FCV commercialization decisions easier, but would not change the basic decisionmaking framework as outlined here.

2.6.1. Pilot-Phase Production and Deployment Decision

The CaFCP's study specifications envisioned a collaborative pilot phase of FCV commercialization in which at least some vehicle manufacturers would join to demonstrate and evaluate approximately 1000 vehicles—i.e., several hundred vehicles each, on average. This pilot phase would assure the commercial readiness of the technology as well as educate and prepare potential users to accept such a major automotive innovation. Pilot phase FCV users could be either fleets of various types, private individuals, or some combination, at the discretion of each manufacturer. Fueling infrastructure in this phase would be small, with possible vendor and governmental assistance, implying no major investment decision requirements for fuel providers.

To meet this pilot-phase goal, each automaker must decide whether to step up investment and risk beyond R&D in order to design, produce, place, and support a share of that number of vehicles in public use. This decision involves a substantial increase in FCV investment due to vehicle design refinement, testing, certification, production capabilities for a small production run, and component-supplier chains, as well as infrastructure development, marketing, user agreements, and monitoring and evaluation efforts. Such a decision will actually be made in stages of increasing commitment and investment, but after the final go/no-go decision is made, the required steps in investment, construction, and deployment will require at least two years before the 1000 vehicles are fielded.

2.6.2. Series-Scale Commercialization and Fueling Infrastructure Decision

Moving from the pilot phase toward full-scale mass production, a second major investment decision must be made on the next step-up to low-volume FCV production and market introduction. This decision step by automakers will provide funds for further vehicle refinement, testing, certification, and the development of higher-volume production facilities. Because of the radical nature of FCV technology and the uncertainties of public acceptance, at least some automakers will stop short of an immediate commitment to funding large-scale mass production capability (e.g., 30-100,000 vehicles per year or more per manufacturer). Instead, the investment scale and risk will drive many automakers to take an interim step to series-scale production (<20,000/yr) while consumer demand builds beyond the early-adopter level. This typically involves adaptation of existing production lines and acceptance of production costs somewhat higher than optimal but with much lower capital investment than required for full mass production. This maintains the flexibility to defer further investment depending on early market response.

For fuel providers, this decision to invest in market introduction preparations will begin a major expansion of the fueling infrastructure to meet minimum FCV user convenience needs. Both fuel provider and automaker investments are interdependent and their decisions must be made in concert.

This decision point may be deferred until at least a year after the start of the pilot phase, in order to provide time for proving the performance and market acceptability of the initial 1000 vehicles and fueling systems. After this decision is made, these production preparation activities will require at least an additional three years before public FCV market introduction.

2.6.3. Mass Production and Fueling Infrastructure Decision

Under this staged scenario, automakers face a third major decision as to whether to invest in moving into larger-scale mass production, marketing, and much higher sales volumes in order to meet growing market demand while minimizing unit costs. This decision phase can involve billions of dollars in new investment for each automaker and its suppliers. After the decision is made, this step's activities will require at least three years until mass production can begin.

A crucial factor in this scenario is the manner in which the FCV market and the fueling infrastructure mature. Automakers need a sufficient market to justify mass-production vehicle launch—but this market may depend in part on the number and distribution of fueling stations, which must be minimized in order to manage the investment risks for the fuel suppliers and marketers. (Note that this dilemma may not arise in the case of gasoline-fueled FCVs, depending on the fuel specification required; see Chapter 6 for details.) Resolution of this conflict requires a compromise in geographic coverage and user convenience.

3 Commercialization Issues for All Fuels

3.1. Overview of Key Shared FCV Commercialization Issues

Many of the requirements for FCV commercialization are the same for all four fuels in this study. These shared elements, including some with differences only of detail among the fuel choices, are presented in this chapter. The subsequent four chapters present separate discussions of the remaining FCV commercialization challenges that are unique to each fuel. Exhibit 3-1 presents the shared commercialization issues and challenges identified and addressed in this study. The most difficult challenges requiring early consideration are indicated in **boldface** type.

Exhibit 3-1: Commercialization Challenges Common to All FCV Fuel Types

Shared Issue Topic	*Specific Issues and Potential Challenges*
FCV Technology Readiness	**On-board reformer delay in commercialization** Alternatives to avoid commercialization delay More detailed assessment of technology status
Market Development: Pre-Commercialization Pilot Phase	Pilot phase rationale Vehicle market type Locations and dispersion of vehicles Selection of specific fleets
Market Development: Initial FCV Introduction	Pilot phase market development needs Market introduction phase customer targets **Broader marketing challenges** **Early strategic communications**
Societal Benefits and Governmental Support	Air pollution and greenhouse gas emissions Other environmental benefits Other societal benefits **Facilitating governmental support**
Public Health and Safety Concerns	Resolving potential offsets to societal benefits

(continued)

Fueling Infrastructure Requirements	Pilot phase fuel choice Market introduction fuel choice process Upstream fuel supply and transport Pilot phase fueling infrastructure Pilot phase stations: number and type Rate of retail station construction Local regulatory requirements
Infrastructure Costs, Risks and Financing Requirements	Pilot phase infrastructure financing **Market introduction infrastructure financing** **The role of governments** Private industry and financial institutions
User Costs and Financing	**Defining the fuel price goal** Fuel price stability
User Support Services	Vehicle insurance coverage Emergency response capabilities Servicing and garaging requirements
The 100,000 Vehicles/Year Alternative Scenario	Major factors in accelerating FCV sales

In the following specific assessments, challenges and solutions are described within each major commercialization topic. Where appropriate, pilot phase and broader commercialization phase versions of these issues are presented separately.

3.2. Fuel Cell Vehicle Technology Readiness

3.2.1. On-Board Reformer Delay in Commercialization

Will commercialization timing be determined primarily by remaining FCV technology challenges?

Yes. Assessments of on-board reformer and fuel cell technology development challenges were excluded from this study's consideration, under the directed assumption that manufacturers will be able to develop and produce the vehicles by the time all the other commercialization challenges, such as fueling infrastructure, can be provided. This is a significant exclusion, since the study's reviews of all commercialization factors suggested that development of market-viable vehicle fuel cell and reformer technology will be the most difficult challenge. The early FCV market introduction targets tentatively announced over the past few years by several automakers appear unlikely to be met, primarily because of these on-board technology challenges.

Although there are still significant challenges in fuel cell cost, systems integration, and controls, the principal technical obstacle appears to be the development of practical and cost-effective on-board reformers (i.e., for liquid fuels) to produce the hydrogen required by the fuel cell. This is due not only to the inherent technical complexity of the reforming processes but also to the unique challenges of the on-board environment. This holds for all liquid fuels, although methanol reforming is inherently less technically demanding and may be more advanced in its development to date. Reforming of conventional gasoline appears to be somewhat more difficult, although its proponents claim a high degree of R&D success. But for all on-board fuel reformers, major challenges of economic feasibility remain even after technical success is achieved.

3.2.2. Alternatives to Avoid Commercialization Delay

Are there strategies that could avoid or minimize such a commercialization delay?

There are. Because of the higher infrastructure cost and on-board storage limitations of the compressed hydrogen FCV option, there is substantial reluctance among automakers to full-scale commercialization based on that choice. However, the direct hydrogen FCV option is simplest and will be ready for public use earliest, because the HFCV's off-board hydrogen production reforming (and/or electrolysis) will use more readily achievable technologies. To meet the vehicle sales milestones set for this study as early as possible, even if developers wish to focus their longer-term light-duty FCV commercialization strategies on the use of on-board liquid fuel reformers it may be advantageous to rely on direct hydrogen fuel cell technology for the first few years of field testing and even the initial low-volume market introduction phase. This strategy would accelerate the introduction of FCVs while allowing more time for the development, testing, and (if competitive) introduction of on-board reformer-based technology and its infrastructure.

A second strategy that may be available is to begin public pre-introduction field testing with on-board reformers that are functional but still too costly for commercial use. This approach will be avoided, however, unless there is a clear short-term path to acceptable economy. Without such a path, in addition to prior assurance of good technical reformer performance, the automaker would be risking an unknown delay in moving to broader commercialization or incurring substantial financial losses on the initial vehicles sold.

3.2.3. More Detailed Assessment of Technology Status

Should the on-board reformer and related technical development status be more closely assessed in studies such as this?

This is impractical now even though such information would be illuminating. It could easily be suggested that this study should be broadened to include more consideration of the differences in on-board and off-board technology challenges (including fuel cells, reformers, compressors, etc.), cost versus achievable price, and risk of developmental failure or delay among the different FCV fuel types. This position is based on the argument that this factor will be a major differentiator among the fuel types, so that excluding it presents an incomplete and misleading view of the differences among the candidate fuels.

However, the CaFCP's wish to avoid such vehicular studies and comparisons at this point remains appropriate. The necessary information for such assessments is largely—and necessarily—proprietary. The CaFCP's approach effectively avoids either compromising the proprietary R&D and business plans of individual automakers or producing results that are naively uninformed on the realities of those automakers' developmental efforts and plans. Each of the automakers can view this study's results in the context of their own vehicle development status and costs, producing an overall picture of challenges, needs, and opportunities as well as their financial implications.

Other stakeholders, such as fuel providers and governmental agencies, can develop their plans and policies based on this study's more general results plus industry information on FCV introduction schedules. Stakeholders can also refer to two independent mass production cost assessments for fuel cells and on-board reformers conducted by contractors to the US Department of Energy (DTI and ADLittle), along with other ongoing periodic fuel cell and reformer technology assessments by US DOE and their national laboratories that are conducting state-of-the-art research on these technologies. As technology development proceeds, this information base will grow richer and more details will become available.

3.3. FCV Market Development: Pilot Phase

As noted earlier in this report, the CaFCP specified a 1000-vehicle pilot phase as the first major step to be assumed in this study of FCV commercialization. This did not imply any intent or plan to conduct such a pilot phase or for specific CaFCP member companies to participate. Instead, this pilot phase was rather a hypothetical scenario intended to dramatize the appearance of FCVs and allow assessment of the pros and cons of such a collaborative demonstration approach.

3.3.1. Pilot Phase FCV Demonstration Rationale

What challenges does the CaFCP's possible "pilot phase" address?

Motivations include both technology assurance and public acceptance. The current 2001-2003 FCV development and testing phase of the CaFCP involves a small (although gradually increasing) number of research vehicles. Most of these will not be true production prototypes, particularly since not all the required technology has been fully developed yet, and their numbers will be too small to provide adequate field verification of such a radical departure from conventional vehicle technology. Automakers have confirmed that these current efforts must lead to improved technology and more production-ready prototypes, followed by more extensive demonstration efforts to refine technical features and assure market readiness.

The initial pilot phase of FCV commercialization specified for this study envisions placement of 1000 or more vehicles in the hands of a broad range of users. This 1000-vehicle pilot phase is an exploratory concept, and does not suggest industry capability, commitment, or plans for any such joint effort. Such a pilot phase is to be interpreted as an initial option for each automaker rather than a precise requirement prior to actual commercialization. Each automaker will make its own decisions as to whether, when, and to what extent they will participate in such a test phase. But a substantial public field trial phase may be needed both to adequately develop, test, and refine the vehicles in a variety of applications as well as to develop the confidence needed in FCVs by the public as well as public authorities and fuel providers before a larger-scale commercial introduction. This phase will need to be at least two to three years in length in order to build adequate technical assurance and public interest plus have time to make and test solutions to any problems encountered.

The 1000-vehicle number is a rough approximation. The pilot phase can be effective with fewer vehicles, and the actual number will depend on the number of participating manufacturers as well as their individual objectives. All the automakers will tend to hold their individual operating results proprietary, and each may wish to have 100 or more vehicles in operation to assure reliable results and effective pre-market visibility—so 1000 or even more vehicles may actually appear during the pilot test period. Some manufacturers may enter the pilot phase either before or after any given start date, depending on readiness and individual strategic considerations. It is also possible that one or more manufacturers may elect to accelerate this test period and introduce their commercial vehicles early, with little or no time dedicated to the pilot phase. In any case, coordination among OEMs will be limited by competitive considerations, so that in effect several independent fleet trials could be underway at the same time. However, coordination on issues such as fueling infrastructure, safety regulation, and public incentives are in the best interest of the public as well as all participants.

3.3.2. Pilot Phase Market Type Selection

Who should be the types of FCV users during this pilot period?

The emphasis should be on fleets, both government and private. There are many pilot phase user choices, including many types of fleets and various categories of individual private users. Some of the factors in this strategic decision include the following:

- Relative ease of placing vehicles with appropriate users and missions
- Ease of vehicle performance monitoring
- Opportunities for technology refinement and replacement as needed
- Economy and ease of evaluation of fueling approaches
- Convenience of user feedback
- Avoidance of potentially misleading or premature media exposure

The fleet choice: This study concludes that the choice should be selected types of fleets for the first year or two, with a possible limited expansion to other fleet types and some private individuals before formal mass market introduction three or more years after the start of this phase. It will be necessary to protect the initial FCVs from misleading publicity and to build a positive image while the pre-production prototypes are being refined and proven. Fleet use is an effective way to do this as well as to minimize the initial infrastructure costs and risks, since refueling can be centralized at relatively few locations. While this initial fleet-focused pilot phase is going on, a coordinated public education effort will be needed as well as construction of low-volume FCV production capability and related fuel delivery infrastructure for broader commercialization.

Types of fleets: Many types of fleets can be included for this phase. Included in the definition are facilities of some automakers themselves, where central refueling stations could be located and whose employees could be given incentives to use FCV prototypes in their daily commute and other travel in addition to business uses. These are in fact the expected first pilot-phase participants, and need not be limited to California locations. FCV fuel providers (e.g., including natural gas and electric utilities as well as liquid fuel providers) and other stakeholders (NGOs and public agencies) may also present controlled FCV pilot testing opportunities, particularly if located near other participating facilities so that fueling facilities can be shared.

A second tier of pilot-phase fleets could focus on large auto fleets with functions such as bank couriers, government pools at all levels, and large school districts. These fleets would be chosen for their ability to absorb relatively large numbers of test vehicles, control the orientation and assignment of drivers, and perhaps provide a fueling site.

Government fleets should be considered but reliance on them should be limited. This fleet type involves many vehicles (e.g., 70,000 in Southern California, according to SCAQMD), but experience in other alternative fuel vehicle introductions has shown major difficulties in securing the necessary funding and achieving the approvals needed on a timely basis. Rental car fleets show promise but also limitations, despite their large numbers, high turnover, and central fueling facilities: Their users are very short-term, daily use for some customers may exceed the maximum range limits of the pilot phase FCVs, maintenance capabilities tend to be limited, and cooperation in data collection may be difficult and highly variable.

Non-fleet participants: Broader involvement of private individual users may be added but should be done with caution. Using the broad range of appropriate fleet types, in the pilot phase there should be little need to move beyond fleets to private unaffiliated individuals. Some automakers may find it desirable for marketing purposes to offer some carefully selected individuals the opportunity to participate late in this phase and to use such individuals in initial marketing campaigns.

This approach causes no difficulties with the overall pilot phase, so long as such a strategy does not require more interim fueling stations. For example, at least one company is developing a small electrolyzer to produce and deliver compressed hydrogen into an FCV at a private residence overnight. This creates an opportunity for carefully screened drivers to test FCVs with home refueling rather than adding more public fueling stations at this early stage.

3.3.3. Pilot Phase Locations and Dispersion

Where would such a pilot phase take place?

A larger market than Sacramento will be needed for 1000 FCVs. The pilot phase cannot be dispersed statewide, due to the need for economy in vehicle monitoring, service, and refueling. At the same time, the area must be large enough to place 1000 vehicles into appropriate settings and missions without undue delay or other difficulty. Although the CaFCP's vehicle support facility is in Sacramento, where there are large state light-duty fleets, experience in prior alternative fuel vehicle demonstrations has shown that the State's vehicle procurement funding and flexibility are limited. Other public and private fleets in Sacramento can be expected to be limited in size, vehicle types, and function similar to those in similar small metropolitan areas elsewhere. If the hypothetical 1000-vehicle target for the pilot phase were to be used, it would almost certainly require a larger market due to this probable lack of an adequate and responsive fleet population. Such a large program would require at least some of this pilot test to be sited in one or more of the state's largest urban areas: the San Francisco Bay Area, San Diego, or the central Los Angeles area.

This would substantially expand the early effort needed in fleet market research, analysis, education, and negotiation. It also expands the extent and cost of fueling infrastructure and local code enforcement coordination. Action needs to begin several years before such an actual pilot phase to assess the fleet market opportunities and to gain the commitments of all major participants including automakers, fuel companies, public health and safety infrastructure providers, legislative and regulatory authorities, local permitting officials, and the fleet operators themselves.

3.3.4. Specific Fleets Selection and Participation

How will specific customer fleets be selected and sold on the pilot phase?

For any such pilot phase, efforts must begin early to identify appropriate individual fleets and their concentrations in specific areas in cities. This may be done separately by each automaker, but some coordination and sharing of information on fleet locations and needs is highly desirable, especially with respect to potential shared FCV refueling requirements.

The pilot phase would require fleets with highly specific characteristics, which will eliminate most fleets from consideration. This study identified a general lack of fleet characterization data that could be used to identify fleets with attributes appropriate to pilot phase FCV placement. Such characteristics include fleet size by vehicle types, refueling approach and facilities, garaging locations and types, uses and mileage for FCV-relevant vehicles, space for FCV refueling facility, vehicle acquisition practices and capabilities, and management attitudes toward alternative fuel vehicle use and test program involvement. Development of such data, at least within areas of interest for the pilot phase, should be undertaken as early as possible.

Marketing to such fleets, once identified as possible candidates, is best undertaken by individual automakers. Government authorities may find this an opportunity to assist and assure this process through incentives such as financial assistance in fueling station placement, FCV and R&D tax credits, and assistance in meeting or modifying local regulations as appropriate.

3.4. FCV Market Development: Initial Market Introduction Period

3.4.1. Selection of Appropriate Initial Markets

Who are the most promising early FCV customers?

After the pilot phase, there are several alternative customer-type targets for the initial FCVs to be available to the public. Some of these include the following:

- More commercial and governmental fleets
- Auto rental fleets
- General public—unrestricted
- General public—restricted

Continued emphasis on commercial and possibly governmental fleets would be the simplest and least costly approach, both in marketing and infrastructure development. This strategy would also be the slowest path to market development, since it covers only a small fraction of the types of light duty trucks and autos that are most likely to be the first FCV models. This slow pace would mean continued losses for automakers, although infrastructure development could be more cautious and less risky.

A transition into auto rental fleet use is more promising, since it would be a much broader market and also exposes many potential future auto buyers to FCVs. Obviously not all rental car users would find the early FCVs appropriate, for reasons of vehicle preference as well as range. However, central fueling facilities would be possible at larger rental outlets and would meet the needs of many rental car customers for whom long range is not an issue.

Both government and commercial fleet markets represent relatively small vehicle populations, and also delay opening the ultimate market—the millions of individual vehicle owners. There is no reason not to include the fleet markets in any initial commercialization effort, but restricting initial FCV sales to these fleet markets would be the slowest path to any significant volume such as the 40,000 vehicles/year milestone that this study addresses. That milestone demands a strong focus on the individual user market. But should that public market be restricted, either geographically or with respect to user characteristics? Yes: An initial geographic limitation is reasonable as a means of balancing user convenience with the need to allow the fueling infrastructure to develop at a sustainable pace.

This suggests a staging of FCV introduction, both among California urban areas and nationally (or internationally). Introduction could occur in the Los Angeles area first, for example, and then expand to San Diego and San Francisco over the following year or two. Market introduction outside California could begin in a similar manner, involving other fuel marketers to begin gradual infrastructure development in those regions. This approach also expands the automakers' FCV production and sales to economically sustainable levels sooner.

No automaker-imposed restrictions on the customers themselves should be needed. Even early FCVs can be expected to have ranges and performance comparable to conventional vehicles, so the initial customers need only be informed about the temporary limits on fueling locations as the infrastructure grows. The result is an initial FCV marketing strategy in which the pilot phase's fleet market is expanded and broadened especially into auto rental fleets, but the principal marketing emphasis shifts immediately to the general public—first in one major urban area, shortly afterward to the other urban areas both in California and elsewhere, and finally to the remainder of the state.

3.4.2. The Market Coverage Problem

Will the initial FCVs reach enough market segments?

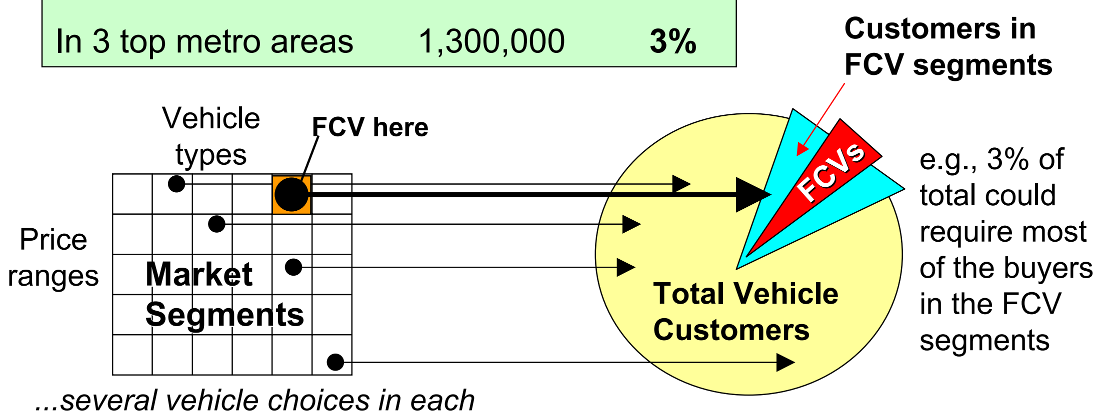
In the context of an expected next-decade California light duty vehicle sales level approaching 2 million vehicles per year, the 40,000 and 100,000 vehicle annual sales milestones are small total market penetrations: two and five per cent respectively. But FCVs will not yet be available to meet the needs of many market segments (e.g., people needing a mid-price sedan rather than a small expensive sports coupe), due to production complexities and costs; models tend to be added gradually as demand grows. This means that for the specific market segments served by the initial FCV models, market penetration will need to be very much higher than the 2-5 percent--possibly even a majority share if only a few models are available.

As illustrated in Exhibit 3-2, this is exacerbated by the need to restrict initial FCV sales to the more dense urban areas in order to reduce the number and cost of fueling stations (details in a later section of this chapter). This is a difficult marketing situation, particularly in the context of the several hundred conventional vehicle model choices now offered with many appropriate to each specific market segment.

To respond effectively to this challenge, a highly effective marketing campaign will be essential. As discussed in Appendix A, the unique consumer benefits of the FCV must be stressed, although an initial premium price will be difficult to sell.

Exhibit 3-2: The Market Penetration Challenge

For autos & LD trucks	2010	FCVs
Statewide sales	1,800,000	2%
In 3 top metro areas	1,300,000	3%



Such a campaign could position the FCV as the superior "car of the future" technology, with no loss of customary features and some unique added qualities of value to consumers. Points could include the following:

- **Competitive conventional values:** responsive driving performance, cutting-edge styling, and all accessory conveniences
- **Innovation and uniqueness:** Uniquely powerful and economical electric power capabilities for both on-board and off-board uses, including unprecedented ones; maybe also the refueling system, if appropriately distinctive and futuristic via design and GIS. (See Appendix A)
- **High 21st century status:** possibly a government-reinforced appeal to "good citizen" values based on pioneering self-image linked to fuel economy, reduction of foreign oil dependence, low emissions, and global environmental (translated as self and children) protection.
- **Reassurance:** Superior fuel economy, low total ownership cost, and reliability due to fuel and upkeep economies (fuel, service, repair, insurance, guaranteed lease cost or buyback)

To launch the FCV effectively it may also be necessary to “value-package” the initial FCV with added features and marketing tactics that are normally either offered only at extra cost or are not available at all. As discussed in Appendix A, possibilities are many, including all the free services already offered on many premium vehicles plus additional features such as GPS, insurance, and guaranteed trade-in values, all for no cost.

3.4.3. Selection of Initial FCV Models

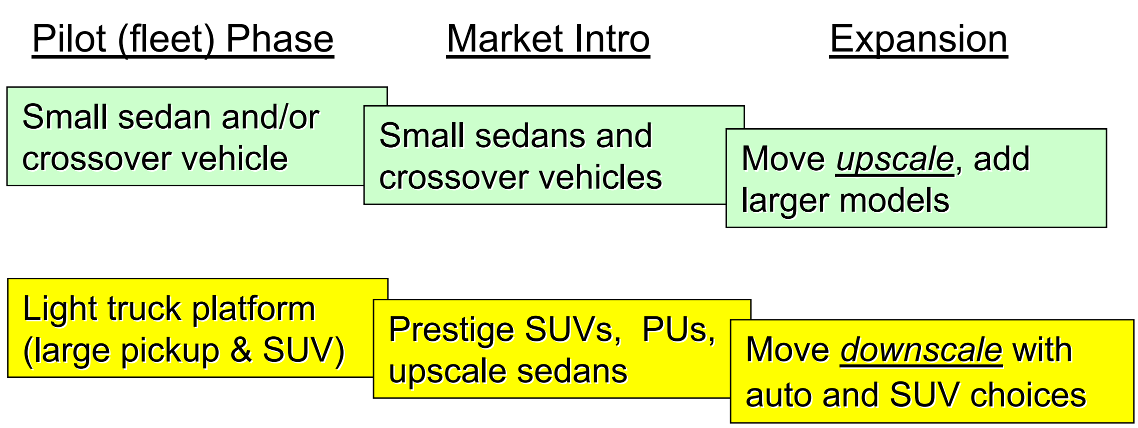
What types of vehicles are most appropriate as initial FCVs?

As with any major consumer-product innovation, the initial customers will include many people with an innate interest in new technologies and the self-image and status they may confer. In marketing jargon, these people fall into standard categories variously termed "early adopters," "innovators," and "enthusiasts." They tend to be above average in education and income for their ages, as well as more often single (young) or retired (older) than with children at home. Their interests often include style and status as well as vehicle performance and conveniences. By mid-decade they may be less interested in family sedans, vans and large SUVs and more interested in upper-market personal cars and the emerging "crossover" vehicles. They will be relatively easily convinced to accept the risks of new technologies because of their strong interest in the benefits they perceive.

There are two problems with this characterization. First, it is at odds with the needs of most pilot-phase fleet customers for no-frills moderate-price sedans and light trucks, and second, the expected early-adopter individual market cannot absorb enough new FCVs to reach the 40,000 vehicles/year California milestone. This suggests that for the pilot-phase FCV marketing to fleets, either adapted conventional small sedans or standard pickups might be the most appropriate pilot phase products rather than early versions of all-new FCVs designed for the subsequent individual market. This phase could use "gliders" from standard ICEV production lines, and would provide a distinct transitional phase. It would also avoid premature exposure of the later public-market FCV models and styling, and provide more time for their development.

Even if all-new FCVs are used in the pilot phase, quite different strategies are possible, as shown in Exhibit 3-3.

Exhibit 3-3: Examples of Initial FCV Model Selection Options and Pathways



These choices will be jointly determined with the initial market segments and therefore will greatly affect potential early FCV sales volumes. Each has advantages, but there is no obvious best approach. The automakers will determine their vehicle model strategies individually, based on their own market research and platform economics. Differences in their strategies will help to broaden the range of options available and engage more market segments.

As for the size of the early-adopter market, before the 40,000 vehicles/year milestone can be reached it will be necessary to "cross the chasm" to appeal to more cautious buyers who are otherwise similar to the usual early adopters. For the mass-market phase, the upper-market personal cars and performance sedans should suffice, but to appeal to more mainstream buyers the availability of models should broaden to include middle-market prices. In addition, the competitive and risk-reduction aspects of the marketing package should be emphasized.

3.4.4. Strategic Communications and Public Attitudes

What sort of public education effort is needed to assure public understanding and support for early FCV introduction?

A coordinated strategic communications program is essential. Public education and market development efforts for all types of FCVs must focus on gaining awareness and support for the benefits of FCV infrastructure and vehicles. This could contribute to a broader public-private campaign positioning hydrogen as "the fuel of the future" for many stationary uses as well as vehicles. In addition to safety, the personal and environmental benefits of FCVs will need to be stressed through a cooperative public education program. This program could be jointly supported by government and the auto industry. Individual efforts should be coordinated to assure a clear message about FCVs and their fuels.

The needed communications program must first of all be strategic: That is, it must focus tightly on activities that are most productive in assuring and accelerating each major step in FCV commercialization. This requires strategic planning to identify the greatest needs and most productive responses. For example, news media and opinion leaders may be among the most important initial audiences due to their ability to educate or to misinform the public. Their public interpretations of FCV performance and environmental benefits can help accelerate FCV acceptance, but if wrong or otherwise misleading they can also greatly impair commercialization prospects—as has sometimes occurred with other alternative fuel and battery electric vehicles.

Media strategy at this early phase would seek to educate key reporters in the societal value of the long-term FCV vision and also plan prudently for defensive responses to misleading stories on aspects such as FCV costs, safety, performance, and environmental threats. Similarly, political leaders at all levels may need to be major initial communications targets since their informed perspective is essential to their support for legislative initiatives to encourage FCVs. In contrast, education of the general public, civic organizations, and schoolchildren may not yet be so strategically important.

This strategic program is crucial and needed well before the pilot phase. Due to the inevitably growing media attention on FCVs by that time, a more aggressive mass market-targeted campaign will also be needed within two to three years of actual market introduction (i.e., early in the pilot phase). That campaign should continue through the first few years of mass market sales, alternating with periodic panel-type market research to gauge the development of public attitudes.

3.5. Societal Benefits and Government Support

The introductory costs of FCV commercialization may be too high for private industry to recover in a reasonable business case. If so, government incentives may be required to reduce investment risks or cover some share of those costs directly or indirectly. But governments too need a reasonable return on their investments, in the form of credible societal benefits. Such benefits may include environmental protection and a variety of other responses to societal problems and needs. This section's purpose is to illustrate the nature and range of such benefits. Estimation of their societal value is beyond this study's scope and is properly the purview of public policy analysts and policymakers.

3.5.1. Air Pollution and Greenhouse Gas Control Advantages

Are fuel cell vehicles really going to be environmentally superior to conventional or hybrid vehicles?

The answer here appears to be yes, although the four different FCV fuel technologies, depending on the fuel as well as its source and well-to-wheel pathway, have widely varying environmental benefits. These fuel-specific effects, including their local pollutant emissions, greenhouse gas (GHG) implications, and other "multimedia" effects throughout the full fuel cycle, are summarized in the specific assessment chapters (4-7) with further details in Appendix B. In this study's analysis of best-available data, all FCV fuels surpass the local emissions-reduction capability of projected lightweight gasoline hybrid vehicles which are in turn superior to similarly-configured future all-ICE vehicles. This same conclusion applies also to greenhouse gas emissions for all fuels other than gasoline--for which GHGs may be approximately equal to those for the best gasoline hybrid vehicle configurations. Thus FCVs of all fuel types appear to be environmentally superior to gasoline hybrid vehicles.[2]

---

[2] Interest and investment in diesel have expanded greatly in recent years, especially in Europe, for both ICEVs and future hybrids fueled by diesel. Detailed simulations by DTI (ASHRAE paper 982496) have shown that diesel parallel hybrids may have lower greenhouse gas emissions than all FCV fuel types, and recent results from a new simulation study by General Motors and Argonne National Laboratory support diesel's superior GHG performance. However, even the best projected diesel hybrids can meet only the least stringent future US Tier 2 criteria pollutant emissions standards (e.g., NOx) and are considered by many experts to be unlikely to become realistic light-duty vehicle options in the US within a decade or more. We acknowledge the

While each FCV will generate less local pollution than similar future ICEVs or hybrids, and direct hydrogen FCVs will be classified as true zero emission vehicles, all FCVs will generate some pollutants and greenhouse gases as long as the hydrogen is derived from hydrocarbon fuels. This may be a problem if the mass media continue to associate FCVs with zero emissions of local pollutants and GHGs. Early public education efforts must address this issue in order to avoid unjustified disillusionment with the initial FCVs, stressing the role of those early FCVs in opening a *pathway* to possible later zero emissions. Eventually, virtual elimination of emissions and GHGs will begin to be possible only if and when hydrogen or methanol begins to be derived from renewable energy sources.[3]

These improvements in environmental protection are expected to provide the primary rationale for the society—both via government incentives and private expenditures—to incur the high developmental and commercialization costs of FCVs. This is particularly important if these benefits are judged to be needed early enough that FCV commercialization must be accelerated. The differences in apparent environmental benefits among the near-term FCV fuel types, as well as differences in their ability to facilitate a later transition into the vision of a renewable-energy economy, may result in different levels of societal support for the initial introduction and acceleration of those alternatives.

Despite these generally positive environmental findings, this study's analysis of available FCV environmental impact studies indicates a scarcity of reliable data and large unexplained variances among the studies of each fuel's estimated impacts. In addition, some types of impacts have not been systematically studied at all. This situation necessitates a strong dose of humility and caution in this study's conclusions. FCV environmental impact is a topic deserving of further primary research as soon as possible.[4]

---

diesel's fuel economy advantage, as well as continued European emphasis on diesel technology refinements, although in this study gasoline parallel versions are assumed to be the standard US hybrid configurations for many years, further diesel technology improvements may create a new baseline standard for FCVs to exceed.

[3] Conventional wisdom suggests that rational profit-maximizing automakers will adjust the emissions performance of their conventional vehicles to just meet the applicable regulatory standards when combined with their FCV sales, thereby yielding no net reduction in regulated local emissions (and GHGs, if such standards appear). But the regulatory process is also adaptive, and targets for any year tend to be influenced heavily by technological advances such as FCVs, such that the existence of FCVs in the fleet will result in sooner-tightened standards.

[4] Based on this study's early identification of the importance of this issue, US DOE and Argonne National Laboratory staff took an important step in this direction with some extensive sensitivity testing of emissions scenarios using their GREET model. Selected results were subsequently incorporated into this study's findings.

3.5.2. Other Environmental Benefits

Are there other important environmental benefits of all types of FCVs?

When in use as a significant fraction of the vehicle population, FCVs will provide a variety of other environmental benefits, including the following:

- Reduced vehicle noise and vibration for occupants and nearby populations
- Reduced motor oil spills and disposal into groundwater and streams
- Reduced gasoline tank leakage and resulting groundwater contamination (except for FCVs using future pump grade gasoline)
- Creation of a long-term pathway toward an environmentally sustainable transportation energy future based on renewable natural resources

3.5.3. Other Societal Benefits

What non-environmental societal benefits may be attributable to FCVs?

These factors differ somewhat among different FCV fuels, although are broadly applicable to all. This study included no detailed examination or attempt to scale such benefits, but they appear to be significant and deserving of serious consideration in the development of public policy toward FCVs.

- Reduced dependence on scarce fossil fuels (due initially to the FCV's higher energy efficiency, although some FCV fuel alternatives may offer additional renewable-source benefits increasing over time)
- Reduced reliance on foreign fossil fuel source nations and cartels, with benefits both in reduced fuel price instability and the international tensions due to competition for limited fossil fuel resources
- Increased national energy diversity (except for gasoline FCVs)
- Reduced property damage, injuries, and fire from fuel accidents (details in specific alternative fuel assessment chapters)

3.5.4. Facilitating Governmental Support

Are the societal benefits of FCVs sufficient to justify the high levels of governmental support that may be required for accelerated commercialization?

This study's limited examination of FCV benefits suggests that they are sufficient. This study does not attempt to monetize or otherwise weigh the broad range of combined benefits of FCVs. However, even the limited evidence presented here for long-term air pollution and greenhouse gas improvements alone may provide justification for substantial state and federal government participation in overcoming major challenges such as infrastructure cost and FCV technology development difficulties. The full range of societal benefits deserves further study and incorporation into future public policy debates.

3.6. Public Health and Safety Concerns

3.6.1. Resolving Potential Offsets to FCV Societal Benefits

Could FCVs present new or exacerbated hazards to the public?

All potential FCV hazards are fuel-specific and are covered in those chapters. In this study, the topic of public health and safety excludes the effects of FCVs on benefits such as reduced air emissions and greenhouse gases due to vehicles. Those benefits are covered in the previous section on societal/environmental advantages. Public health and safety concerns here focus instead on potential problems that have been suggested as attributable to FCVs such as fuel hazards including groundwater contamination, new fire sources, and human ingestion of toxic fuels. Some of these effects create important FCV commercialization issues related to public health and safety concerns, but all appear to be fuel-specific. See the sections on this topic in Chapters 4 through 7 for assessments of these issues, specific challenges, and solutions.

3.7. Fueling Infrastructure Requirements

3.7.1. Pilot Phase FCV Fuel Choice

What fuel will be used in any early pilot phase, and will the difficulty of that choice slow commercialization progress?

Fuel choice for a pilot phase should emerge from a consensus that may now be developing. A possibility now under consideration by the US auto and fuels industries is the interim adoption of compressed hydrogen for a possible (but as yet unscheduled) joint pilot phase. Such a choice would imply no long-term commitment to that pilot phase fuel technology; its intent would be only to accelerate any such pilot phase by using existing compressed hydrogen fueling and storage technologies familiar to all automakers.

This approach would allow more time for the development of on-board reformers and other fuel technology options. It also allows the FCV concept to be tested independently of the more complex fuel processing options that could be introduced later as their technologies mature. If a pilot phase is significantly delayed, however, the expedience of the hydrogen option could disappear. The result could be either a technological advance that produces a different dominant fuel choice or a more confrontational market-based competition among fuel choices. At that point, a small-scale competition among fuels could be beneficial in demonstrating and narrowing the options before market introduction.

3.7.2. FCV Initial Market Fuel Choice Decision Process

How can the initial FCV fuel choice challenge be overcome so that both automakers and fuel providers can depend on one another's commitment?

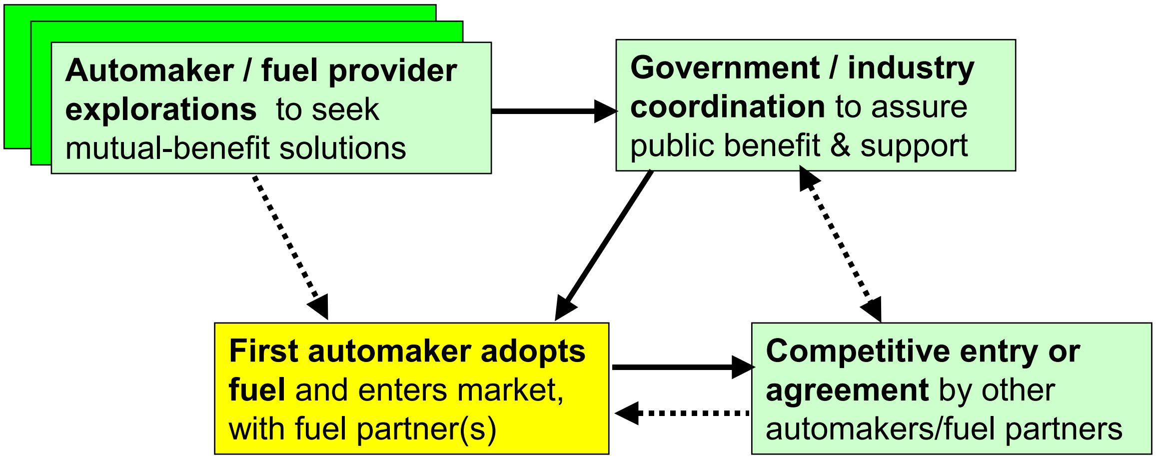
This fuel choice for FCV market introduction will occur gradually through technology development and industry negotiation. The fuel choice issue is the major topic of interest to many participants in the emerging FCV industry. However, this study makes no judgments as to a "best" FCV fuel type. Further, no single entity or group such as the CaFCP will select the fuel of choice for FCVs. Instead, a dominant fuel will emerge in stages through the interplay of interests and capabilities in a competitive market. It is possible, in fact, that more than one fuel alternative may be in commercial light-duty vehicle use at the same time, particularly in any pilot phase and even initial mass-market introduction.

This competitive process is likely to be active during the pilot phase. It will involve many current and future players. Each will be seeking to advance competing specific fuel and fueling technology alternatives, probably continuing even after the initial infrastructure investments are made. Those players will include automakers, fuel cell-related technology developers, fuel suppliers and marketers, and a variety of legislative and public agency authorities. If some key fuel providers, automakers, and public authorities can begin to work both separately and in cooperation to create viable business cases for both a fuel and the vehicle, the necessary financial commitments will follow to produce the necessary vehicles and fuel infrastructure for at least one specific fuel choice.

Exhibit 3-4 on the following page illustrates a possible deliberate stepwise approach to FCV fuel choice. Exploratory discussions such as shown in the top left box of Exhibit 3-4 are now underway among some vehicle and fuel providers. Potential private financial partners and governmental funding authorities also need to be brought into such discussions as soon as possible, as shown in the next box, in order to build complete business cases including possible roles for legislative and regulatory incentives as needed.

Government agencies interested in accelerated FCV commercialization should take the initiative to encourage and join in such explorations at the earliest possible time. Only with such early cooperative efforts, focused on alternative paths to the necessary commitments and backed by action (e.g, legislation on incentive strategies), can the fuel choice issue be influenced and accelerated effectively.

Exhibit 3-4: Outline of Possible FCV Fuel Choice Process



If pursued diligently, this process can improve the joint vehicle/fuel business case to the point that one automaker and its fuel partner(s) can make the formal commitments necessary to move into the post-pilot production and market introduction stage as shown in the bottom-left box. Once that step is clearly made by one competitor, others may either follow or choose a competing fuel path, thus leaving the fuel choice to the consumers.

3.7.3. Upstream Fuel Supply and Transportation

Will adequate fuel sources be available for FCVs without major new efforts?

Generally, yes, although with some variations as noted in the specific fuel assessment chapters. The volumes of fuel needed to reach the interim California milestones for this study are extremely small in comparison to current vehicular fuel usage. If considering only those milestones, adequate supplies of most fuels will easily be available and delivered without major difficulty or investment. (Ethanol may be an exception, as discussed in Chapter 7.)

In order to evaluate the overall feasibility of each fuel pathway, this study also included general assessments of the longer-term impacts of widespread FCV adoption using each fuel. Those assessments are included in the specific fuel chapters. The necessary reserves of petroleum and natural gas are adequate for the FCV alternatives that require them, as are the potential renewable fuel options if enough development time is allowed. Some specific refining and transportation challenges do exist, however, and are treated in the four chapters on fuel-specific challenges.

3.7.4. Pilot Phase Fueling Infrastructure

How many pilot phase fueling stations will be needed, and how big an investment will be required?

With an emphasis on fleets and facility-sharing, very few stations will be needed. In this phase, each OEM will be operating its own pilot FCV program. Each could also make its own arrangements for fueling infrastructure, but the advantages of collaboration appear to be greater than those of complete independence. This sharing of fueling facilities could substantially reduce costs for all, since each automaker's vehicles could be refueled at all stations. Fewer stations would be required, assuming at least some limited cooperation in fleet and refueling-site locations. Although more than one fuel provider could be involved, as well as more than one fuel delivery method, unified planning and management of the refueling system would further reduce costs. Such a joint effort in fueling infrastructure would allow a more open sharing of the initial experiences for the benefit of the entire industry's preparations for the later and larger-scale phases of FCV commercialization.

Once one or more fuels are selected for initial use, the initial pilot-scale infrastructure will be quite small. If 1000 vehicles were spread among 50 fleets, with each fueling facility serving at least 5 fleets in reasonable proximity, even a small fueling capability would suffice. For example, a fueling station with a small above-ground storage tank and single dispenser could readily serve the resulting average of 100 vehicles: Only about ten would require refueling on a typical day, which could be done in about two hours even if arrivals were that closely timed (e.g., workday start and ending hours). This suggests that 10-20 mostly shared fueling facilities could suffice even if two urban areas are involved, so long as fleet sites are reasonably clustered. The likelihood of such clustering is supported by the typical city zoning of specific areas for such functions.

The investment cost for providing this interim infrastructure is estimated in this study to be under $3 million for hydrogen (with most pilot phase stations using temporary tube trailers for delivery to specially developed sites from centralized production facilities) and about $1 million for each of the liquid fuels. Operating costs will vary widely and delivered fuel costs will differ substantially. At 10,000 miles per year per vehicle, a pilot period's annual *conventional* fuel cost would be in the range of $500-700K (30-40 mpg equivalent); FCV fuel costs could be up to several times that amount, despite the vehicle's much greater fuel efficiency, because of the diseconomies of small-volume production as well as inefficiencies of the interim fuel delivery methods. Thus the total cost of providing and operating the pilot phase fueling system for its three-year duration is estimated to be in the $5-10 million range.

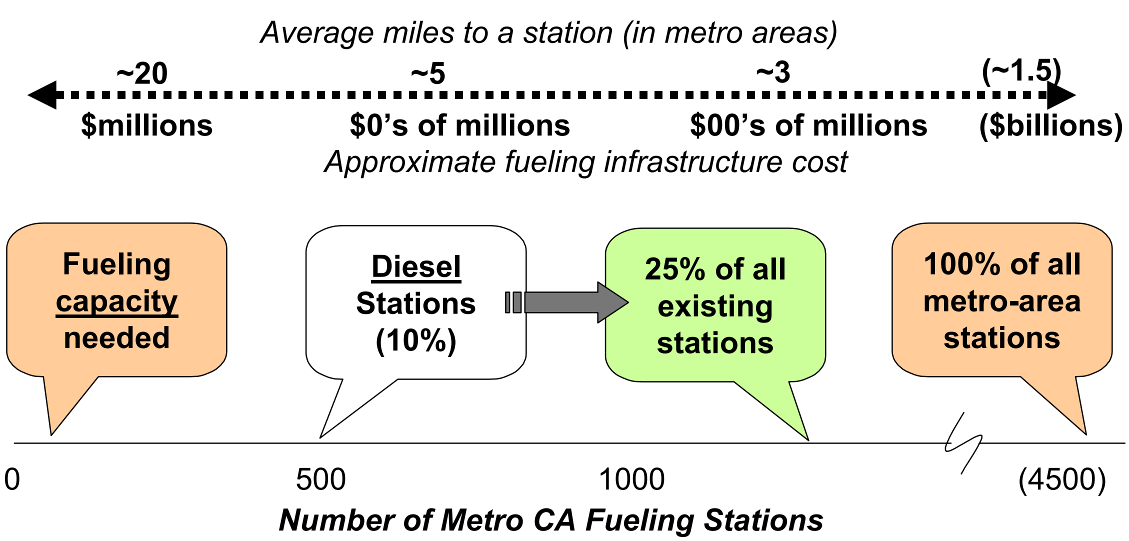
3.7.5. Fueling Infrastructure for Market Introduction

How many fueling stations will be required by the time the 40,000 vehicles/year milestone is reached?

Five hundred is probably a minimum, with many more required later. For FCV commercialization to begin, the pilot phase fueling infrastructure must transition quickly into a much larger system based on initial experience, technology advancement, buildup of market demand, and competitive interest. Assuming a gradually expanding geographic area of FCV sales and fueling infrastructure coverage, there could be a need for at least 100 stations during the first 2-3 years of low-volume public market introduction, serving perhaps 2-3,000 FCVs in use in the first year of market introduction and 5-10,000 the next. If augmented by on-board GIS station-locator capabilities in all FCVs, this should provide minimally adequate geographic coverage. Continuing fuel delivery cost support will also be needed for the growing but still small FCV population. These station installations will be more costly (~$90K each for liquid fuels and $400-500K for hydrogen; see details in Chapters 4-7) than the earlier "temporary" ones to be used in the pilot phase, due both to higher fueling capacities and more permanent construction.

As FCV production and sales expand, within a few years after the initial public introduction of FCVs all technology for more economical fuel production and delivery should be ready for use, and a much larger scale-up of the fueling infrastructure must be in place. Opinions vary widely on the required minimum number of fueling locations needed to sustain a mass market FCV introduction, with some major fuel providers urging 25% or more of the existing 9,500 retail gasoline stations in California and at least one public agency suggesting that far fewer than 500 should suffice. Exhibit 3-5 illustrates this dilemma.

Exhibit 3-5: Estimating the Number of FCV Fueling Stations Needed



This study proposes a compromise between optimal user convenience and that high early infrastructure cost. About 10% of California's filling stations now offer diesel fuel in addition to gasoline, and about half of the existing stations are in the three major core urban areas where the early FCVs are here proposed to be sold and used. Using diesel availability as a minimum standard, some 500 fueling sites could serve the FCV population in those areas. This includes a small number of stations on major connecting routes across the state.

Effects of varying this number of early fueling sites are easily estimated. Particularly during the early years when fuel volumes per station are low, the total infrastructure capital and operating costs are almost linearly related to the number of stations. As the economic analyses later in this report will show, higher infrastructure costs in this initial period will be very difficult to justify.

Because of the need for continually improved user convenience in order to expand FCV sales, this infrastructure density is seen in this study as a minimum, even allowing for the future use of on-board satellite-GPS driver information systems to help locate the stations. More solid empirical evidence is needed on the number of stations actually required to encourage enough early FCV buyers to meet either the 40,000 or 100,000 vehicles/year sales milestones.

After these initial FCV sales milestones are reached, it is assumed that sales rates will continue to increase. Many more stations would continue to be added as FCV sales, fuel volumes, and statewide coverage increase. The costs for these later stations can be expected to remain at the same constant-dollar levels unless the average station's FCV fuel vending capacity increases substantially.

3.7.6. Rate of Fueling Station Installation

Can the required number of stations be sited, designed, and built quickly enough?

Timely installation of the 500 stations is a major but feasible task. This task includes survey and selection of sites, completion of designs, procurement of permits, equipment, and skilled tradespeople, and the actual installation time to complete modification or construction of 500 fueling stations to be equipped for an FCV fuel. If for example the market penetration trajectory up to 40,000 vehicles per year requires 4 years, as shown in Exhibit 3-6, an average of about 10 station completions and expenditures on the order of $1 million or more will be required each month.[5]

---

[5] This time period is illustrative only and implies no expectation or capability.

Exhibit 3-6: Rates of FCV Fueling Station Completions

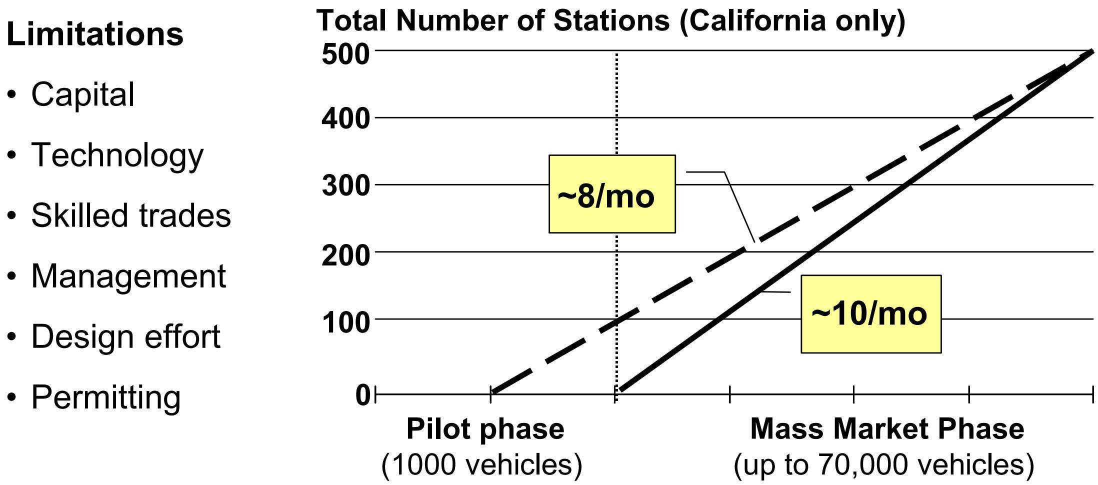


Exhibit 3-6 also indicates that if station completions must begin a year earlier in order to have a minimum of 100 in place before FCV market introduction, the required average completion rate declines to 8 stations per month—although the earlier investment would increase overall financing costs.

This task would be divided among the several major fuel marketers to be involved in FCV fuel retailing in California. Also, for perspective, 500 stations are far fewer than the many thousands of similar-scale underground gasoline tank and vending equipment replacements done throughout California in recent years, primarily over a ten-year period, in response to a state government requirement to eliminate old and leaky tanks. Certainly these FCV fueling facilities, especially for hydrogen, would each be more complex than a single gasoline tank replacement. This comparison suggests that with multiple large fuel suppliers involved, each would have a manageable even if difficult task comparable to what they have already proven able to carry out.[6]

After the first few years of market introduction, when the FCV population is growing fast, the rate of infrastructure construction may become a limiting factor. This study's focus was on the initial transition from FCV introduction to an interim mass-market penetration milestone (defined by the CaFCP as 40,000 vehicles per year in California sales). During those earliest years, the rate of fueling station construction is driven mainly by the need to establish a minimal acceptable level of station density rather than adequate fueling capacity, since there will be few vehicles but a need to serve a large

---

[6] A potentially exception to this conclusion arises if the "Energy Station" option were to be extensively used, combining a hydrogen FCV fueling station with a larger-capacity reformer and stationary fuel cell for distributed electricity generation, to be discussed later in the hydrogen chapter (4).

geographic area. However, the study's financial modeling results demonstrate that within the following few years, when the FCV population could be growing at a very high rate—e.g., 80,000 or more per year in California alone—it may become very challenging to meet the fast-growing demand for fueling capacity.

The illustrative market development assumptions used in this study for those later years resulted in a very high rate of fueling activity per dispenser (well beyond conventional practice) despite an increasing rate of construction and an improving financial case. Although such "problems of success" are beyond this introductory study's scope, we note that this topic requires further analysis and scenario planning. For example, more dispensers might be added more quickly at existing stations, while reducing the rate of new station development—reducing both cost and construction effort while providing more dispensers.

3.7.7. Local Code Enforcement Requirements

Will local refueling site permitting requirements delay or prevent the installation of the necessary refueling infrastructure?

Avoidance of permitting problems may require technical assistance to local officials. Much of the local permitting of potentially hazardous new fuel transport, storage, processing, delivery, and use is dependent on individual interpretations of the applicable regulations. However, local jurisdictions will be unfamiliar with FCVs and their fueling station requirements, and although some new code revisions may be available by then for FCV fueling stations, most familiar codes and standards were developed for industrial rather than vehicular uses of fuels such as hydrogen and methanol. As soon as cities are selected for pilot phase FCV deployments, work may need to begin to educate local permitting officials on the facts of FCV infrastructure, appropriate codes, and their interpretations, and to achieve any local code enforcement changes needed.

This work will need to spread throughout the State's target areas for broader public FCV introduction as soon as initial lessons can be drawn from the pilot phase efforts. Although varying greatly in degree, this issue applies to all four fuels. Such local code enforcement assistance is an activity appropriate for coordinated industry effort rather than individual fuel providers or automakers. It must begin well in advance of the pilot test phase, and can be a collaborative effort among state agencies, automakers, and fuel providers. Funding for such activities could be via several means, including state grants and/or contributions by individual participants.

3.7.8. Longer Term Infrastructure Implications

What are the logistical implications of longer-term hydrogen infrastructure expansion both within and beyond California?

Expansion of the initial 10% of California urban-area stations to a possible 25% of all stations statewide would expand the earlier number (i.e., 500) by a factor of four, or 2000 more stations. If these were to be completed within about 15-20 years after the initial

500, the average annual number added would require a completion rate about the same as the 10/month in the initial period.

Expansion of the FCV market beyond California during that same period would increase total infrastructure requirements proportionally. A nationwide FCV fueling infrastructure at an estimated 25% of all filling stations could eventually require 20,000-25,000 station installations. The construction term can be assumed to be similar to that for California, i.e., 20-25 years including the initial introductory period. This implies an installation rate in the 100-per-month range. This level of highly specialized national construction activity will need further study of skilled labor requirements, equipment production, and siting and installation capabilities. Highly standardized installations can help to minimize both the costs and difficulties of this infrastructure development.

3.8. Fuel Infrastructure Costs, Risks and Financing

Fuel infrastructure risk and financing is a topic of concern to proponents of all fuels because of the high early investments required and the long period of market development before those initial investments become profitable. Also, these early investments could be stranded later due to emergence of improvements in competing fuel technologies or other factors. Financing needs and sources may differ by phase, and will be facilitated through a variety of approaches.

It is very important that users of this study clearly understand its limitations of purpose and approach to development of infrastructure cost and revenue estimates. The study's purpose was to show what will be needed to successfully commercialize FCVs using each of the four fuels independently—including a financial scenario that balanced cost and performance to yield an indication of the risks and returns. This proved to be very difficult. The limited "success" criterion which proved most achievable with a reasonable set of input assumptions for each fuel was *the achievement of a positive annual net cash flow after debt service within ten years following commercialization.*

The assumed input values to the study's financial model achieve that goal for each fuel. However, it must be emphasized that these are not forecasts but rather only illustrations of what could be required to achieve the study's goal. This study's authors encourage its users to study the effects of alternative sets of assumed values of key parameters such as numbers, capacities, and costs of fueling stations, rate of FCV market penetration, conventional gasoline price, other fuel feedstock prices, etc.

3.8.1. Pilot Phase Financing

Will there be difficulties in securing and justifying the funding needed for the pilot phase fueling infrastructure's installation and operation?

During the hypothetical 1000-vehicle pilot phase illustrated in this study, the costs of installation and operation of the estimated 10-20 fueling facilities will be small compared to those to be incurred later in actual FCV commercialization. There will be several pathways to funding for this pilot phase, including coverage of any above-market delivered costs of the fuel. This is an ideal opportunity for a demonstration phase for competing hydrogen generation technologies, with both vendor and government support in addition to possible funding from the fuel providers and facility operators.

As demonstrations, the estimated 10-20 site installations needed could be financed in part through federal and state grants based on the long-term environmental benefits of FCVs. The delivered fuel price to fleet vehicle users during this period could be either free (as an incentive to participate, because the total quantities would be relatively small during such a pilot phase) or equivalent to the price of the gasoline replaced (i.e., fuel neutral), and the cost differential could also be government-subsidized. The gasoline equivalent annual fuel cost would then be approximately 1000 vehicles x 12000 mi/yr x $2/gal / 30mpg = $800,000 or $800 per vehicle per year.

These estimated amounts show that in comparison with the initial FCV costs or even the routine costs of conventional gasoline fueling infrastructure maintenance, the estimated $5-10 million level of cost for initial pilot-phase fueling system construction, operation, and fuel should not be a major challenge.

3.8.2. Mass Market Fuel Infrastructure Financing

How can the costs of the 500-station fueling infrastructure and beyond be financed?

During this phase the fueling infrastructure must be expanded rapidly, as noted in the previous section—both in California and elsewhere. Continued government incentives to investors and operators may be necessary, although this need will vary among fuels depending on the costs and risks involved. Such incentives can include various loss insurance programs, direct grants, enhanced investment tax credits or future loss writedowns, and below-market long-term loans.

Individual major energy marketers may come forward to invest in adaptation or construction of fueling facilities, but if the financial risks are perceived as too high for single-company sponsorship the automakers, fuel providers, and/or state government may be able to make use of the financial markets to hedge the risk with futures contracts or to seek other investors and form one or more consortia to share the early market risks and later payoffs. Negotiations among potential sponsors need to begin even before the pilot phase, as do efforts to develop sources and mechanisms for fuel price subsidies.

If this investment risk is too high, the subsequent FCV public introduction phase would shift to one of several infrastructure commitment alternatives. Possibilities for this phase include the following:

- **Fuel provider hedging or inter-industry support.** One or more fuel providers could use the experience of the pilot phase and its evidence of OEM commitment to elect to enter the FCV fuel delivery market as a competitive initiative. This may still require hedging or futures strategies for bulk fuels, or support from the auto industry or government, since the scale of investment (and presumed initial losses) would be at least an order of magnitude higher than for the pilot phase.

- **Government risk insurance strategies.** This involves recognition of the fuel providers' financial risk and the potentially weak business case for FCV infrastructure versus the long term public benefit that may arise from a societal shift to FCV use. Both federal and state authorities could assist in encouraging private investment in FCV infrastructure by providing financial investment stop-loss guarantees or capital loans that could be forgiven or discounted if an early fuel technology were to become prematurely obsolete. This approach keeps the investment decisions within the private sector but shifts some of the financial risks to the public sector in acknowledgement of the long-term public benefits.
- **Investor consortium.** In this financing strategy the financial community would be engaged to create either an IPO or a consortium of diverse large long-term investors to buy into the infrastructure business, possibly with an existing fuel provider as one partner—thereby making the investment no less risky but smaller in scale for each party. Diverse business models can be developed for this general approach, including risk reduction through FCV production guarantees or direct financial involvement by the OEMs.
- **Government backed alternative fuels corporation.** For maximum reduction of industry risk, the state or federal government could charter and back a new public corporation to build, operate, and eventually sell the FCV fuel delivery infrastructure. This corporation could also be a joint public-private venture under a variety of business organization strategies.
- **Regulatory-driven infrastructure.** In the absence of sufficient free-market response to the fuel delivery infrastructure investment opportunity, the state or federal government could use the public policy benefits of FCVs to justify moving infrastructure development requirements into the existing ZEV regulations or parallel new FCV regulations. This would require the automakers to assure adequacy of infrastructure, spreading the unrecoverable initial costs over the entire conventional vehicle sales volume in California for a transitional period.

3.9. User Costs and Financing

3.9.1. Defining the Fuel Price Goal

What constitutes a fair basis for any FCV fuel price to the consumer?

This study assumes conservatively that FCV fuel expense should be competitive with the gasoline fuel cost for a similar conventional vehicle. The overriding operating cost issue for FCVs is likely to be the retail price of whatever fuel is required. Other costs such as insurance, maintenance, repairs, and depreciation may vary somewhat from those of conventional vehicles, and significant divergences from customary costs, while not anticipated, can be covered through special warranty provisions. Fuel presents a special dilemma: The user has to pay for it very often. The actual costs of providing any of the candidate fuels for FCVs during the first several years will be much higher than that of conventional gasoline, primarily because of inefficiencies caused by the relatively small amounts of FCV fuel to be provided. There may also be a long-term cost differential. Thus if the retail fuel price were to reflect all costs, the prospective FCV buyer may interpret this as a significant disadvantage.

It must be acknowledged that FCVs will require less fuel than conventional vehicles, due to higher efficiency. At the same Btu price, this would *reduce* the user's annual fuel cost, or permit a higher per-Btu price while preserving a *competitive* annual user fuel cost. But the importance of the annual fuel budget to the prospective FCV buyer is unpredictable. Past consumer response to fuel price fluctuations has been complex. Although the reality or expectation of substantial non-crisis fuel price increases has not generally produced a comparable reduction in travel, it has tended to encourage the purchase of more fuel-efficient vehicles as a way to reduce overall fuel expenses.

Even this response is unpredictable, as demonstrated by the unbroken popularity of fuel-intensive SUVs through recent large variations in gasoline price. However, due to the anticipated challenges of marketing early FCVs, a conservative position is warranted. This study's analysis therefore assumes that the early FCV user's per-mile fuel price (or annual budget) should be reliably competitive with that of gasoline for conventional and hybrid vehicles. This implies that some FCV fuel price protection mechanism will be needed for at least several years, and not only in California.

Fuel price volatility, including that of conventional gasoline, is an important related concern for FCVs. Recent events with energy prices illustrate substantial and unpredictable swings in fuel prices. Examples are high ethanol prices due to MTBE replacement demand, high electric power prices due to limited generation and transmission capacity, gasoline price fluctuations due to a variety of market forces, and high natural gas prices due to high demand and interstate pipeline capacity bottlenecks. The viability of each fuel may well change several times before and during early FCV marketing. Drivers will be dissatisfied with any FCV fuel--and by extension, with the FCV itself--if the price is too high, but they will define "too high" primarily by comparing that price to that of gasoline. Thus any FCV fuel price intervention should focus on controlling that differential rather than the absolute price of the FCV fuel.

3.9.2. Fuel Price Stability

How can future prices of the various non-gasoline FCV fuel options be pegged to that of gasoline, despite often divergent market price fluctuations in all fuels?

Innovative fuel futures market transactions may be a possible solution. In this study it is assumed that the user must pay no more for fuel than required for a comparable conventional or hybrid vehicle. This conservative assumption allows a higher per-Btu price but not a higher annual or per-mile cost. As noted in the previous section, this assumption is based on the importance of avoiding negatives in the marketing of FCVs, as well as the study team's judgment that any noticeable FCV fuel premium above the current average vehicle fuel expenditure of nearly $1000 per year is a significant negative to most potential buyers. If future consumer research supports this position, a mechanism may be needed to tie the price of methanol, ethanol, hydrogen, and gasoline-like FCV fuels closely to the moving price of future conventional gasoline.

The early market for FCVs (as well as that for all alternative vehicle fuels) will be too small and unique for at least several years to rely solely on fuel supplier competition to protect the consumer. A mechanism is needed to avoid unexpected but disruptive FCV fuel price increases relative to standard gasoline. One such mechanism would be to link any governmental support of FCV fuel price to the wholesale price of gasoline. This support of the FCV fuel price would increase when gasoline prices are low (or when the FCV/gasoline price differential is high) and decline as gasoline prices rise relative to the FCV fuel. Eventually, as FCV fuel volume grows and its cost declines toward its bulk Btu value—through efficiency and technology innovation as well as increased competition—the subsidy could be withdrawn altogether.

A more efficient mechanism may be for fuel retailers (or government, or automakers, on the retailers' behalf) to negotiate long-term fuel supply/feedstock contracts or tradable futures that for a small premium may assure future prices. This is a highly developed art in the commodities trading world and may—with adaptations—be applicable to this situation. Such long-term contracts and hedging transactions normally apply only to short-term positions and definite quantities. However, financial markets tend to find ways to innovate mechanisms to meet new needs: For example, there may well be qualified players willing to estimate and accept future price differentials between gasoline and another FCV fuel, and then to adjust those estimates as needed to apply to successive incremental volumes of future fuel deliveries. Such transactions may benefit from government-backed stop-loss insurance or other risk reduction assistance, which would require justification based on the societal value of the FCV.

3.10. FCV User Support Services

FCV user support services include insurance, emergency response, and servicing and repair plus the operation of a resale market to protect the buyer's investment.

3.10.1. FCV Insurance Coverage

Will the user's FCV insurance costs and coverage availability be any different from that of conventional vehicles?

Probably not, unless early experience justifies a change. According to the Insurance Institute for Highway Safety,[7] the automotive insurance industry can be expected to insure the users of the first commercialized FCVs without regard to their innovative propulsion system. Instead, standard rating factors will be applied: vehicle body type, weight, and cost. Thus the first FCVs will have insurance rates similar to those of

[7] Personal communication

conventional vehicles. The IIHS indicates that there is at this time no bias either for or against any specific FCV fuel type.

As FCV on-road experience grows and data accumulate on insurance costs vs. premiums, the insurance industry will seek to validate the initial rate assumptions and may find reason to either increase or decrease FCV rates relative to those for conventional vehicles. Revised FCV insurance rates and coverages, if necessary, will then depend on the insurance industry's analysis of failure modes and causes, likelihood of incidents, the nature of damage, and relative levels of costs. Both before and during early commercialization it will be important for automakers to open and maintain communications on FCV status with the insurance industry in order to stay aware of their concerns and experience.

3.10.2. Emergency Response

Emergency response is largely fuel-specific, due to the different hazards associated with each FCV fuel type, and is covered in the fuel-specific assessment chapters 4-7.

3.10.3. Servicing and Garaging

Servicing and repair are assumed to be provided by the automakers, with the observation that the quality of such services must be superior as a part of the FCV marketing package; an unusually extensive warranty should also be included.

Garaging safety requirements are fuel-specific and are covered in the specific assessment chapters 4-7.

3.11. Alternate Commercialization Scenario: 100,000 Vehicles, Same Timeframe

What must occur to allow the annual FCV sales in California to reach 100,000 vehicles per year instead of 40,000 by the same time?

In addition to the 40,000 vehicle interim-milestone analysis, the CaFCP requested consideration of requirements for an accelerated commercialization scenario in which an annual rate of 100,000 FCV sales in California is reached in the same (unspecified) length of time. An easy answer would be that all activities must be undertaken sooner and pursued more intensively, but this is unrealistic: The decisionmaking schedule for the 40,000 vehicle milestone is already assumed to be as compressed as reasonably possible. The CaFCP’s intent in specifying the 100,000 vehicle alternative was to gain a better understanding of what other factors could be influenced to expand the market more quickly.[8]

Assuming that vehicle production capacity is adequate, the key factor in achieving a higher sales rate is to appeal to more customers. As demonstrated in an earlier section, the basic 40,000 vehicles/year milestone is itself already challenged by a probable initial lack of variety in FCV models and prices, leading to limited market segment coverage and the need to virtually dominate those market segments to reach the sales goal. With the 100,000 vehicles/year alternative milestone for the same time period, it will therefore be necessary to appeal to a broader range of market segments. This in turn will require more FCV model and price choices at this early stage. A reasonable assumption is that two to three times as many FCV choices must be in mass production in order to achieve this level of market penetration in California.

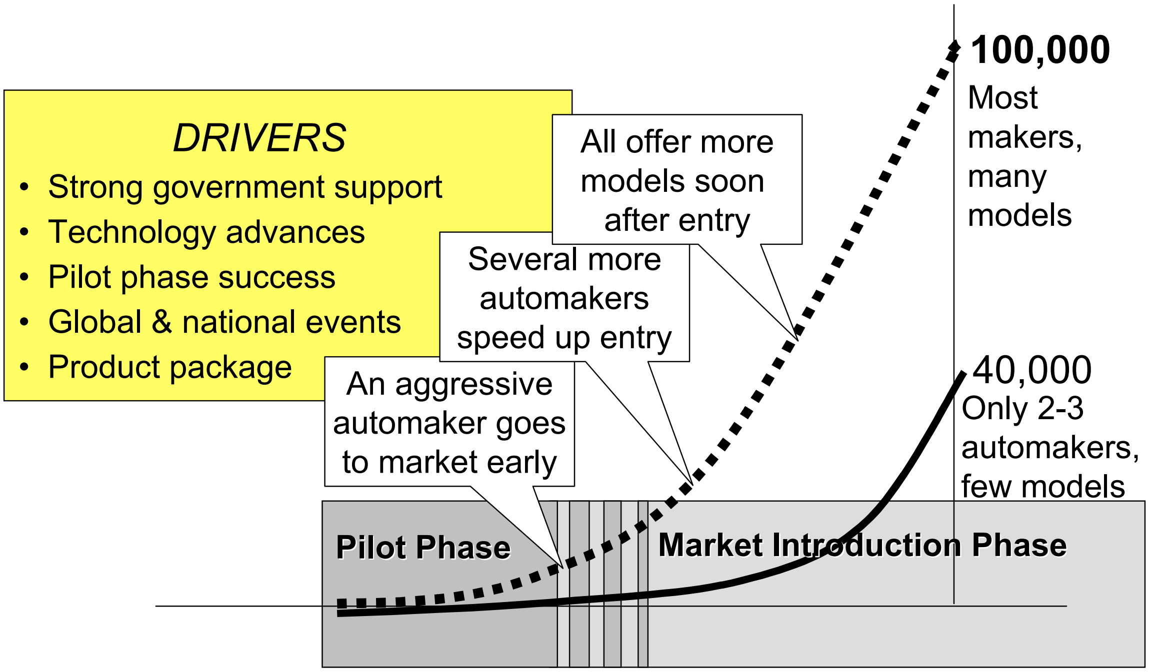
In the basic 40,000 vehicle scenario the sequence of FCV development, production, and deployment activities is assumed to be tightly scheduled already. This more ambitious 100,000 vehicle scenario can then be achieved only by a combination of four additional factors, as indicated in Exhibit 3-7:

1. **Early entrant:** At least one automaker beginning market introduction earlier than assumed in the basic decision sequence, thereby starting market penetration sooner and allowing at least a year for its growth trajectory to go beyond the 40,000 vehicles/year milestone.
2. **More players:** Inducing later-entrant automakers to accelerate their FCV preparations and market entry, thereby providing a broader range of consumer choices at any given time.
3. **Broader range:** Individual automakers finding ways to offer more initial FCV models sooner than in the basic scenario, in contrast to single models gradually expanding to two and three (as with hybrids). For example, the initial multi-use vehicle platform used for an FCV might allow multiple body types or price classes based on that platform to include an FCV option sooner rather than later.
4. **More sales outside California:** If other regional FCV markets are opened in parallel or soon after the California introduction, production volumes needed to meet the total consumer demand will help to cost-justify earlier addition of more models that can then expand the California market. These markets could be either domestic or international.

---

[8] It should be noted that the 100,000 sales rate would very likely be reached in any case within only a year or two after the 40,000 vehicles/year milestone. The marketing "chasm" between the enthusiast-type early adopters and the more cautious mainstream buyers will have already been reached in California by the 40,000 vehicle point, and as long as the consumer's FCV choices continue to expand to meet the needs of more market segments, the rate of increase in FCV sales should be on a rapidly increasing trajectory. Parallel sales in markets outside California should help to provide this broadening of FCV choices.

Exhibit 3-7: Key Determinants of 100,000 Vehicle/Year Acceleration



This 100,000 vehicle/year scenario also requires a more intensive effort in all commercialization activities. This will be necessary in order to reduce investment risk enough to help induce the three changes in automaker behavior as listed above. Several specific factors (also as shown in Exhibit 3-10) will be most influential in promoting such an acceleration:

- Early and unequivocal demonstration of strong and effective governmental support in both financing aid for competitive fuel pricing and investment risk relief. This is a major opportunity for government agencies to accelerate FCV commercialization.
- Success of FCV technology developments and the pilot phase of market introduction in technical performance as well as media support and public interest. This depends on increased R&D support, including incentives, plus meticulous planning and coordination of the pilot phase.
- Extreme efforts in FCV product packaging with additional features and services to increase differentiation and perceived value in relation to more conventional vehicle choices. This requires substantial additional expense that may be extremely difficult to justify or recover.

Accelerated FCV commercialization may also be triggered by specific changes in external world or national conditions within the next few years. Examples include unsettling new environmental changes such as major visible global warming effects linked to vehicle emissions, major new world political tensions or threats based on growing competition for oil and gas, and unexpectedly large increases in fuel cost, all leading to new fuel economy interest by vehicle users and increased public policy support for FCVs. Although not controllable as commercialization initiatives, one or more of these may induce actions by government or industry that would dramatically accelerate the introduction and market penetration of FCVs.

3.12. Resulting Shared FCV Commercialization Strategy Elements

3.12.1. Initial Activities Required for Pilot Phase Decision

For the hypothetical pilot phase as specified for this study, initial activities must focus on meeting the conditions needed for auto and fuel supplier commitments to participate. Those commitments must occur at least two years before the pilot phase can begin. Key activities during this period include the following for each fuel type:

- Refined and improved estimates of environmental benefits through detailed new original research, with stakeholder consensus.
    - …Development and adoption of cooperative FCV introduction strategy by participating automakers, fuel providers, and public authorities.
    - …Demonstration of complete vehicle readiness in terms of reliability, performance, etc.
    - …Development and standards compliance of complete fuel infrastructure system details.
- Fleet market characterization studies and educational outreach as needed.
    - …Assistance to local permitting officials in FCV code compliance.
    - …Negotiation and enactment of needed governmental incentives for infrastructure, fuel, and vehicle costs in both the pilot phase and the broader public introduction and mass production phases.
- Development and deployment of public education and response-monitoring programs under collaborative public-private sponsorship.

3.12.2. Pilot Phase Startup

Several related activities must continue during the two years after any joint decision to have a coordinated pilot phase, to assure that the phase begins as agreed.

- Agreements with users on placement of vehicles (1000 specified for this study scenario), to prove and improve the technology as well as to begin a long-term marketing effort.

  …Limited coordination on topics such as use of fueling facilities, public education, and local government approvals.

  …Largely independent efforts by each automaker, with vehicles focused in commercial fleets as well as local, state, and federal government fleets plus OEMs' own fleets and employees with access to refueling sites.

  …Most refueling sites fleet-run but some may be located to be made available to other fleets as well as the public in future, i.e., at fenceline of fleet yard on public street.

- Motivation for fleets to use the initial FCVs to be provided by policy and backed by subsidy of all costs in excess of conventional operations (both investment and fuel cost as well as repair).

  …Companies get tax incentives for offering pilot test vehicles to employees, in order to get more vehicles per site.

  …All vehicle acquisition to be direct from OEM to fleets.

  …In parallel, secure auto and fuel supplier commitments for broader market introduction both in and beyond California, and start buildup of public education campaign focused on preparing consumers.

3.12.3. Transition to Mass Market Introduction

The goal here is expansion of fleet vehicle and refueling site placements beyond the 1000-vehicle pilot test, using gradually upgraded vehicles based on experience plus new vehicles from OEMs entering the program late.

- Begin placing more vehicles with own (automaker and fuel provider) employees as well as those of commercial and government fleet participants and possibly other employers to offer attractive lease terms for commuter-type uses, in order to get more use of the initial refueling sites at fleet yards.

- Meanwhile, gradually step up the public education campaign by beginning to focus on the successes of the pilot program (e.g., proven in millions of miles of use, survey results showing happy users, reliability statistics, etc.) plus bus and fixed-site fuel cell demonstrations and encouraging anticipation of public release. Consider high-profile FCV racing or endurance demonstrations to build image of competitive or superior quality, reliability and performance. Start "Select Dealer" program to focus training of mechanics, parts stocking, and handling of leases. Focus on creating backlog of both fleet and personal orders beyond capacity, and on conferring high status on FCV users.

- For the alternative 100,000 vehicle/year milestone, at least one automaker may accelerate introduction of vehicles into the public market by up to a year.

3.12.4. Mass Market Introduction and Marketing

The goal of this phase is to ramp up to annual placement of several thousand vehicles as soon as possible—within 2-3 years at most.

- Begin to offer more varied and improved models (on same platform) to broaden market.
- Begin broad public marketing with leasing by select dealers.
- Rely on GPS fueling station locator service and existing fueling facilities plus begin installation of fuel industry-owned fueling facilities (or separate stations as required) with investment risk shared via government and new commercial investment partners.
- Same marketing messages continued, with adjustments per results of interim market research and new product development.
- Continue attractive lease terms, possibly with maintenance and insurance.
- For the 100,000 vehicle target, more automakers enter market early due to governmental incentives and market interest, introduce multiple models, and expand their choices more rapidly during this period.

3.12.5. Mass Market Development

At this stage the goal is to accelerate deliveries for California to 40K (or the alternative 100K) vehicles/year, with more being sold elsewhere and the sales trajectory climbing quickly.

- Begin mass production by at least two manufacturers (four or five manufacturers with several models each for the 100K goal), with variety of models increasing each year.
- Further intensify marketing: Major message at this point may be "the future is now" backed by statements of commitment from OEMs and fuel providers. Continue stressing differential value of on-board electric power for conveniences both on-board and off, maintenance cost, fuel economy, and environment (which may be a much bigger issue by then). Continue effort to confer high status on EV users as future-oriented adventurers with confidence and vision.
- Step up infrastructure development with more fuel provider entrants, some still using investment consortia and/or government participation (based on environmental value) to reduce payoff risk.

4 Hydrogen FCV Challenges and Solutions

4.1. Hydrogen FCV Overview

The on-board storage of hydrogen for light-duty fuel cell vehicles presents some important advantages for early FCV commercialization. The required fueling infrastructure technology, while costly, can be developed readily from current technology. Hydrogen FCVs do not require on-board liquid fuel reforming; this should reduce vehicle cost and complexity as well as the uncertainty of timely reformer development to commercial standards. The widespread access to hydrogen-carrier fuels such as methanol, gasoline, and natural gas in California (once the planned NG pipeline capacity expansions are completed) and other major markets will reduce near-term upstream fuel infrastructure costs, as will the availability of electrolytic hydrogen production once the state's current electricity shortfall is resolved. It also appears possible for enough existing gasoline fueling stations to be permitted and retrofitted to accommodate hydrogen production, storage, and dispensing under existing safety standards, although many existing stations will simply not have enough space.

The HFCV is inherently more fuel-efficient than the liquid fueled FCV alternatives due to its lack of an on-board reformer step. The HFCV is also unique among fuel cell vehicle types in its full ZEV classification. Among other things, this eliminates the vehicle as an emissions control point, focusing instead on the fueling station and resulting in far simpler monitoring and control of vehicle-related emissions. Liquid fuel spills are also eliminated. Finally, the HFCV may provide the most direct path to environmentally sustainable transportation in a more distant future hydrogen/electricity economy based on renewable power generation.

Offsetting these benefits, early fuel cell vehicle commercialization with hydrogen must address a substantial set of challenges. Most important, it appears that there is no practical near-term alternative to high-compression storage of gaseous hydrogen on-board the vehicles. Potential public concerns over compressed hydrogen's dangers, even if unfounded, must be assessed, understood, and allayed through demonstration and education. Compressed hydrogen also has uniquely high fueling infrastructure construction and operating costs, implying a need for substantial government support such as incentives to offset the resulting high fuel price. Finally, its high-volume on-board storage requires serious vehicle space/range /cost compromises that could impair FCV acceptance.

Other hydrogen storage options such as metal and chemical hydrides may reduce the storage volume problems in the future but introduce other problems such as weight, startup time, temperature control, and overall vehicle system efficiency. Hydrides are under active development (e.g., Toyota's latest test vehicle) and may eventually succeed, but currently seem not to be near-term commercialization possibilities. The level of stranded investment risk for compressed hydrogen FCVs is therefore especially high, due to the possible emergence of more competitive technologies either for hydrogen storage or liquid fuel use within as short a time as a few more years. This section presents this study's view of a practical pathway to address these difficulties in direct hydrogen fuel cell vehicle commercialization.

4.2. A Hydrogen FCV Commercialization Strategy

Successful hydrogen fuel cell vehicle commercialization involves many elements, but only a few are unique to hydrogen FCVs. This study's vision of these hydrogen-specific elements includes the assurance of environmental benefits, satisfaction of public safety requirements, evolution of the vehicle itself, its fueling system, infrastructure investment and deployment, regulation and permitting, and the consumer education and market development process. A possible pathway to commercialization for hydrogen FCVs can be summarized as follows. The remainder of this chapter provides further details.

Given the CaFCP's specification of a multi-automaker pilot phase, there appears at present to be no viable alternative to compressed hydrogen on-board storage to begin that phase. Existing technologies and regulations are generally adequate for initial hydrogen production, transport, storage, and fueling. Hydrogen can be provided in a variety of ways for this initial phase of commercialization, ranging from truck delivery from existing central facilities to fueling-site production either using electrolyzers or reformers based on natural gas or a liquid fuel. All these options should be encouraged at this early stage, in order to gain experience with different solutions to the hydrogen delivery challenge, demonstrate costs, and match their benefits to the needs of different delivery sites.

The hydrogen FCV strategy also includes the exploration and possible development of integrated "hydrogen energy stations" that use a local reformer to provide hydrogen to a stationary fuel cell to provide electrical grid or building power (distributed generation, in electric utility terms) as well as hydrogen for FCVs. This unit would also produce excess heat that could be employed for local water or space heating, process uses, etc. This integrated concept would spread the costs of the stationary infrastructure over several different uses, with the goal of reducing costs for all (see for example Lovins & Williams, 1999). Such units would most advantageously be sited in areas of local power grid problems such as overloaded supply lines, high growth, and power quality shortfalls or interruptions, in which the high costs of conventional solutions would allow the energy station's fuel cell to be most valuable. Since the stationary application would tend to be dominant in size, the FCV hydrogen demand could be added incrementally as needed. A variant of this concept places a smaller energy station at an individual home or workplace, using already installed natural gas as reformer fuel and providing high quality power, outage protection, peak-period power delivery to the local power grid when needed, and hydrogen to one or more FCVs with a slow-fill compressor connection.

The initial compressed hydrogen FCV fuel's delivered costs during this low-volume phase will not be competitive with gasoline in ICEVs. The excess costs of the early fleet-focused fueling infrastructure and its operation can be financed through new state and federal tax credits or similar incentives to fuel providers, who need not be limited to present conventional vehicle fuel suppliers.

The future potential of the hydrogen FCV market will readily attract fuel providers interested in early market position. At the same time, early and sustained public education on hydrogen safety and FCV benefits, coordinated among governmental agencies, automakers, fuel providers, and environmental advocates, should be undertaken to correct common misperceptions and build an enthusiastic mass market.

Meanwhile, efforts should be intensified on the development and permitting of key hydrogen FCV technologies for the earliest possible use. Fueling infrastructure requirements include standardized reforming and fueling technologies for economical use at existing gasoline stations. On the vehicles, needed improvements include design for improved accommodation of compressed hydrogen tanks, cost reductions for those high-pressure tanks, and practical metal or chemical hydride storage. When available for broad deployment, any one of these options could greatly improve FCV value and consumer response. Even without these options, commercialization could still continue with less desirable but functional compressed hydrogen fuel supply systems.

The necessary rapid expansion of the hydrogen fueling infrastructure will require a high capital investment based on a very long-term and risky business case. The early investment risks may prove manageable only through substantial and sustained government support. Justification of such support would be based on a policy-level view of accelerated HFCV introduction as a step toward national fuel independence, continued air emissions reduction, and the very long-term environmental vision of a renewable hydrogen economy.

The infrastructure costs for compressed hydrogen deserve special mention here. Skeptics often cite these relatively high costs as the principal reason for dismissing hydrogen as an initial fuel pathway for FCV commercialization. That judgment is too extreme, for at least two important reasons:

- **The cost issue in perspective:** The high costs of the early compressed hydrogen infrastructure may be offset by the likely lower vehicle cost due to elimination of the on-board reformer and fuel cleanup equipment. Some of this cost savings will be offset by the cost of the pressurized on-board tanks, but those costs are expected to decline with further development, production experience, and volume. The resulting net cost savings in the vehicles may prove sufficient to cover the cost of the hydrogen-fueling infrastructure. Further study is required to test this possibility with accurate vehicle technology cost data, which was not available to this study.

- **FCVs as a public policy issue:** Near-term cost is not the only issue. Unless liquid fuel reformers can be improved quickly, FCVs using those fuels may simply not be available soon enough, delaying the market introduction of this important technology. Moreover, in the first few years of FCV use, numbers of vehicles and the size of their needed fueling infrastructure will both be small. Even if compressed hydrogen were later to be displaced either by a less costly liquid fuel approach or by a more economical means of hydrogen storage without high compression, public policymakers may judge the possible acceleration of FCV market introduction by compressed hydrogen to be an adequate public benefit to justify some form of financial assistance.

4.3. Hydrogen FCV Commercialization Challenges and Solutions

This section provides details on the major issues facing hydrogen FCV commercialization, together with specific possible solutions and their implications. These are organized by topic and specific issue, as shown in the following Exhibit 4-1. Specific challenges that proved to be most urgently in need of additional effort are indicated in **boldface type**. Text sections on each potential challenge follow this table.

Exhibit 4-1: Compressed Hydrogen FCV Commercialization Challenges

Topic	*Potential Challenge*
Vehicle Technology	Fuel-related technology readiness
Adequacy of Societal Benefits	Air pollutant emissions levels Greenhouse gas emissions effects **Hydrogen generation pathway alternatives** Multimedia impacts National security implications
Public Health and Safety Concerns	Ignition hazards Invisible flame hazards
Market Development Requirements	Consumer education Product packaging

(continued)

Fuel Infrastructure Requirements	Adequacy of fuel feedstocks Pilot phase fueling technologies **Market-introduction fueling technologies:** • **Onsite reformer-based system feasibility** • **Electrolysis-based system feasibility** • Central hydrogen production and delivery • **Integrated Energy Stations** **Fueling station siting and construction** Longer-term infrastructure expansion
Fueling Infrastructure Costs, Risks, and Financing Requirements	Upstream hydrogen infrastructure costs **Fueling station costs** Delivered hydrogen cost components Hydrogen infrastructure cost projections Infrastructure costs in context Stranded investment risk **Hydrogen business case** **Infrastructure financing**
User Costs and Financing Requirements	Fuel pricing acceptability Fuel price stability
User Support Services Requirements	Garage and shop safety regulations Emergency response

4.4. Vehicle Technology Readiness

4.4.1. Fuel-Related Technology Readiness

What is required for practical hydrogen on-board storage technology to be developed expeditiously to market readiness?

Current hydrogen storage options include 5000 psi compressed gas, liquid, and hydrides; the compressed gas option is already well developed for general use despite its inherent drawbacks, LH_2 is usable but not widely considered practical, and hydrides are longer-term prospects. Research efforts are in progress to improve all three. A more detailed discussion of the options is provided in Appendix G. This section focuses only on compressed hydrogen, due to the longer-term nature of the other options.

On-board fuel storage is a major concern for hydrogen FCVs. Throughout this decade, the mode of on-board storage will almost surely be pressurized gaseous hydrogen, avoiding the energy and cryogenic storage penalties of liquid hydrogen and the unknown developmental delays, excessive weight, thermal management difficulties, and high cost now faced for hydride storage options. Depending on vehicle size and weight, the HFCV will carry between five and ten pounds of hydrogen in lightweight thin-wall cylinders wrapped with carbon fiber. At 5000 psi (the most currently used and generally expected storage pressure for at least the first several years) this will require several times the storage space needed for gasoline for equivalent vehicle range. Some automakers may opt for somewhat reduced range in pilot phase models, commensurate with fleet user needs, in order to minimize that space.

For economy of initial small-scale production in the early pilot phase, at least some manufacturers may use an adapted conventional auto body with the hydrogen fuel tanks in or beneath the trunk. However, the HFCVs first introduced to the public after the pilot phase may instead be designed to accommodate tanks unobtrusively either under the floor or in an extended trunk space. Another option under development is the use of higher compression, which could reduce storage space but also increase energy use for compression.[9] At the same time, the space that would be required for an on-board reformer and its auxiliaries in liquid-fueled FCVs will provide extra room in the HFCV that may be usable for additional hydrogen storage. Clever designers can create unique configurations for HFCVs that capitalize on these aspects while retaining important shared vehicle production commonalities with the manufacturer's ICE and hybrid models. The vehicle's lighter fuel, powerplant, and structural weight will translate to design options for different combinations of higher performance, improved fuel economy, and associated emissions.

4.5. Adequacy of Societal Benefits of Hydrogen

The principal societal benefits of FCVs in general tend to focus on environmental protection improvements and resulting health benefits to citizens. Related questions for hydrogen FCVs focus on the fuel feedstocks and the methods to be used for their conversion and delivery to the vehicle as compressed hydrogen. Other societal benefits include national fuel flexibility and security. All are described in the following sections.

4.5.1. Local Air Pollutant Emissions

What are the expected <u>local pollutant emissions</u> for compressed hydrogen FCV technology options?

Hydrogen is acknowledged as having the lowest possible direct criteria pollutant emissions for vehicles. Hydrogen fuel cell vehicles are placed in the same California Air Resources Board category as battery Zero-Emission Vehicles (ZEVs). This categorization of HFCVs is based on the fact that the vehicle has no potential source of harmful on-board emissions.

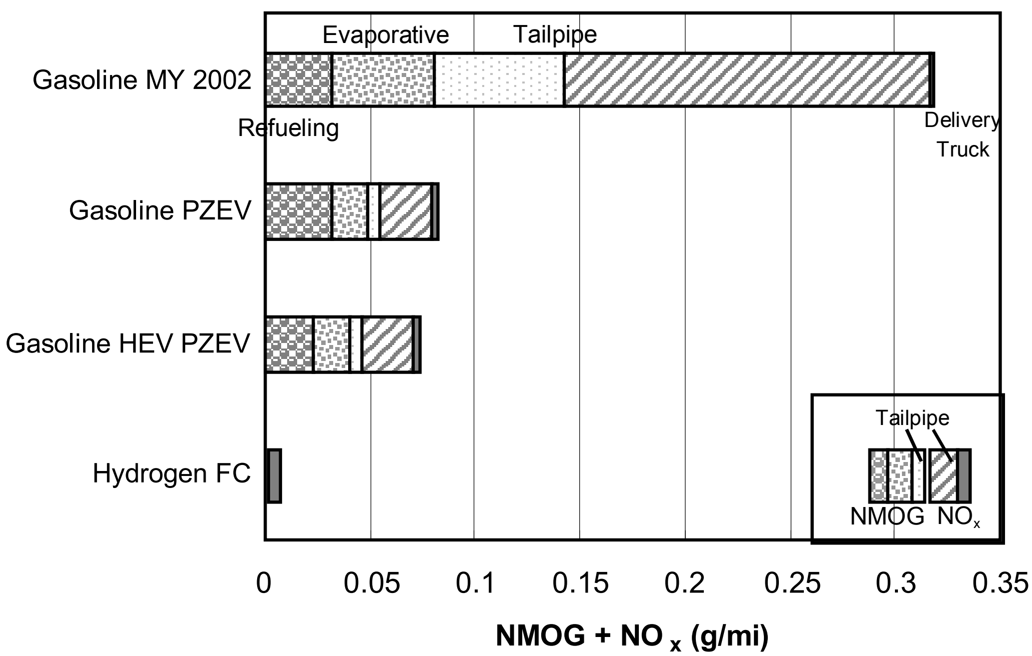
Options for off-board hydrogen generation sources are varied, including water electrolysis and reformation of fuels such as natural gas, methanol, GTLs and some petroleum refinery products. At least in theory, each of these could be used either at

[9] As of mid-2001 some major auto companies were involved in R&D on compressed hydrogen vehicular systems or components with operating pressures ranging from 7,000 to 10,000 psi.

dispersed FCV refueling sites or in large central facilities with liquid or compressed hydrogen delivery to refueling sites. This study focuses on natural gas reformation and electrolysis options at the refueling site, due to prior studies having indicated the probable economic and environmental advantages of these approaches over the central-facility alternatives (e.g., Thomas *et al*, 1998). This study also excludes off-board reformer fuels other than local natural gas on similar economic grounds, since the liquid fuels have been shown to have costs higher than natural gas (Thomas *et al*, 2000 preprint). However, if natural gas prices rise according to some predictions, liquid-fuel hydrogen carriers such as methanol may become attractive options and should be included in any future economic analysis.

Total local emissions attributable to HFCVs depend upon how and where the hydrogen is produced, as shown in Exhibit 4-2. In the case of a reformer at a fueling station, these emissions include the reformer exhaust as well as fuel cycle emissions associated with natural gas distribution and power generation. Vehicle tailpipe emissions are zero and no auxiliary fuel fired heater is required on-board the vehicle—thus removing the vehicle from the emissions control points inventory and dramatically reducing the number of emissions sources that must be monitored.

Exhibit 4-2: Local Air Pollutant Emissions of Hydrogen FCVs vs. Similar Conventional Vehicles



Several data sources confirm the emission levels from the reformer, including tests from a stationary natural gas partial oxidation system that produces hydrogen as well as a phosphoric acid fuel cell with a natural gas reformer. The reformer is the only source of emissions in the fuel cell system (Unnasch, 1998).

Relevant HFCV emissions also include those of natural gas engines used for pipeline delivery of the natural gas to the station site. When the impacts associated with delivering natural gas to the fueling station reformers (marginal basis) are considered, leaks from pipelines and underground storage do not increase with fuel demand. As discussed in Chapter 3, this marginal emission approach has been extensively discussed by California air quality regulators and fuel industry stakeholders, and is the primary metric for evaluating vehicle emissions.

Electricity-source emissions: Production and delivery of compressed hydrogen inevitably uses substantial amounts of electricity. In the near term, electricity-related emissions associated with electrolysis and hydrogen compression can be assumed to come from natural gas-based power generation in California at most hours. Extensive evaluations of similarly sourced emissions associated with EV charging (on a g/kWh basis) have been performed over the years. While there are still significant uncertainties regarding efficiency of the generation mix, depending on the types of power plants and hours of generation, the local emissions are similar to those from reformed natural gas.

Potential indirect emissions: Local HFCV emissions are primarily the marginal emissions from fuel production. However, there are also potential impacts associated with hydrogen production, dependent on the capacity of the natural gas and power distribution system, that are not readily reflected by the marginal emissions. As natural gas consumption increases towards full capacity, there will be pressure to build additional pipelines as well as price pressure on natural gas that may promote fuel switching and conservation. If hydrogen production is integrated with home heating or other co-production options, this effect will be reduced.

Similarly, electric power generation for hydrogen compression or electrolysis adds to the total power demand in California and increases pressure for new power plant construction. While new power plants are an important local siting issue, the emissions from new power plants are generally much lower than those from older facilities. In addition, emissions from new power plants in California are offset with reductions from other sources, although finding emission reductions is challenging in many circumstances.

While these impacts of HFCVs are important, they must be compared with the potential impacts of building new oil refineries, increasing tanker and tanker ship traffic, and other aspects of petroleum fuel use.

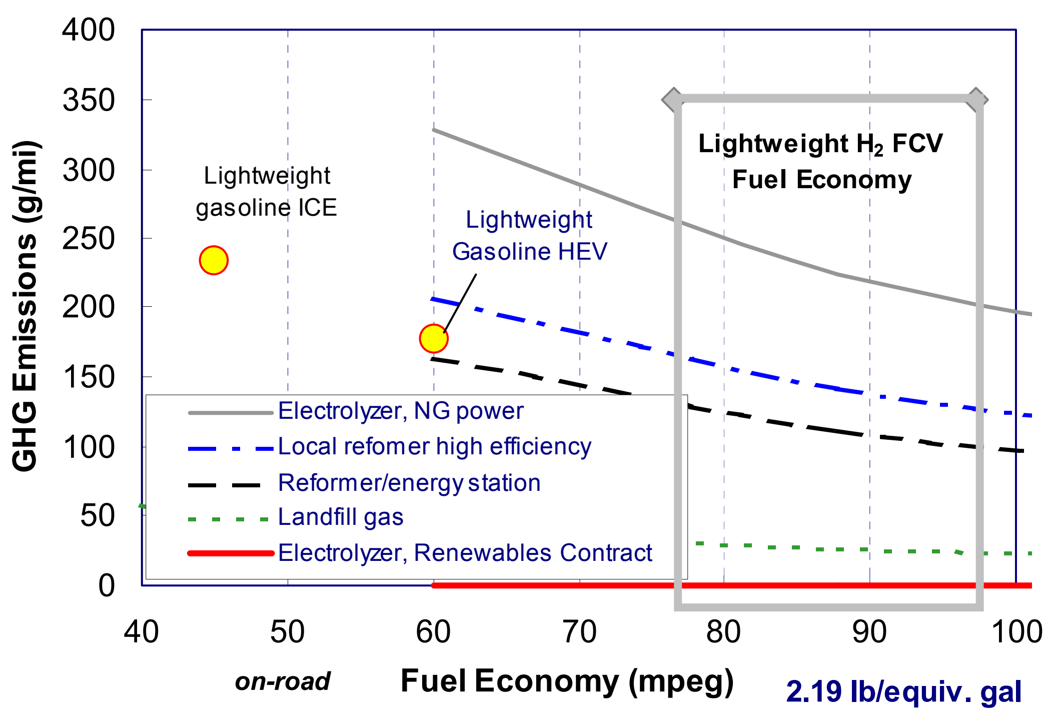
Since hydrogen can be stored, it can be produced at nighttime when power prices are low and avoid the use of power during peak demand periods. This advantage is particularly significant for hydrogen from electrolysis. The opportunity for nighttime hydrogen generation may also help enable markets for green power. For example, developers of wind power could sell their power to users who will be charging their vehicles and thereby generating a fixed demand for the power at night. The additional guaranteed nighttime demand can help the economics of wind and biomass generation resources.

4.5.2. Greenhouse Gas Emissions Effects

To what extent will compressed hydrogen FCVs provide <u>greenhouse gas</u> reductions?

A larger uncertainty for hydrogen is its impact on the production of greenhouse gases (GHGs). Exhibit 4-3 shows this study's estimated well-to-wheels GHG emissions from hydrogen powered vehicles compared to gasoline vehicles, based on a review of available prior studies (see Appendix E for details and sources). The graph is constructed to allow the reader to judge the effect of vehicle fuel economy. While the presentation of GHG emissions allows for the interpretation of any expected vehicle fuel economy, many reviewers of this study have expressed interest in a presentation that reflects the vehicle efficiency improvement for HFCVs.

Exhibit 4-3: Greenhouse Gas Emissions of Alternative Hydrogen FCV



A range of fuel economy estimates is shown as a box in Exhibit 4-3. These values are based on a study performed by the California Energy Commission in cooperation with carmakers, fuel providers, and other stakeholders (see Appendix B for details). This estimated fuel economy range, for a lightweight HFCV, is consistent with the 45 mpg estimate shown for a lightweight gasoline vehicle having similar attributes. Some analysts believe that the HFCV fuel economy value could be as high as 90 mpeg; however, the values presented here are more consistent with carmaker projections.

GHG emissions for all the HFCV options, except electrolysis based on natural gas-based power generation, are well below the European benchmark CO_2 value of 241 g/mi (150 g/km). Reformer-based scenarios are shown only for natural gas. Although liquid fuel reformers were not studied in this analysis, they could also be considered if they prove to be cost-competitive. This could easily occur if relative fuel prices change. For example, the delivered price of natural gas could continue its recent instability and very high prices in California, although for this study it was assumed that NG prices will return to its former range of $5-6/MMBtu and be held there by future LNG competition.[10]

Other options for electrolysis hold promise for lower GHG emissions. In the near term, dedicated solar panels or green power that results in new non-fossil generation could result in low-GHG power generation. Also, landfill gas is a renewable fuel option that is being considered for hydrogen production, although this resource is limited and in demand for electric power generation. In the long-term, a shift to more renewable power would improve the outlook for electrolysis based hydrogen.

Carmakers have many options for reducing fuel consumption, and an assessment of hypothetical vehicle fuel economy may be of limited value. The GHG values in Exhibit 4-3 may prove helpful for policymakers in considering incentives or other regulatory support based on fuel economy expectations.

4.5.3. Hydrogen and Multimedia Environmental Impacts

Will compressed hydrogen FCV technology introduce new problems or improvements in direct "multi-media" environmental impacts on soils, water, and biota?

In this study there emerged no evidence of any challenges for hydrogen FCVs in the form of new multimedia impacts. To the contrary, hydrogen FCVs reduce the existing impacts of the conventional gasoline vehicles that they replace, through elimination of contributions to oil and gasoline spills throughout the supply chain. This aspect thus becomes an additional benefit of HFCVs.

[10] This anticipated gas price decline in fact occurred after the study was completed in mid-2001.

4.5.4. Hydrogen Generation Pathway Alternatives

Do different hydrogen generation alternatives significantly affect the HFCV's environmental benefits?

Hydrogen for initial HFCVs could be produced in a variety of ways. Some would be generated by electrolysis at refueling station sites, with most of the required electricity provided by efficient natural gas power plants operating at the demand margin. Some will be truck-delivered in either cryogenic liquid or compressed gas form from central plants using large steam methane reformers. The remainder would be generated by smaller onsite reformers that still need to be developed. Options here include natural gas, gasoline, methanol or ethanol, although this study focused on natural gas.

Environmental impacts of such choices vary widely, as shown in Exhibit 4-3. However, the immediate emissions and GHG benefits of early hydrogen generation technology choices are much less important than the creation of a hydrogen pathway to long-term large-scale improvements using future technologies.

The electrolysis process may have higher greenhouse gas emissions than hydrogen produced by reforming natural gas directly, as shown in Exhibit 4-3's different hydrogen-source curves. However, scenarios involving a combined business plan linking new wind, solar, biomass-based power generation to electrolyzer power demand would have vanishingly low emissions of all types, including GHGs. Such initiatives would help to accelerate the adoption of those renewable generation technologies and the gradual shift to a future hydrogen economy.

Several environmental improvements in hydrogen production are possible. Lower pressure storage, where possible, reduces the energy requirement for hydrogen fueling, which could result in up to a 10% reduction in GHG emissions. A unique feature with hydrogen for FCVs is that most feasible options involve onsite production. Hydrogen production can benefit by co-location with fuel cell power generation as well as by using waste heat from the hydrogen production process itself, where burning of natural gas would otherwise be required.

A more elaborate method of reducing GHG emissions would be to sequester the CO_2 associated with fuel production. Excess CO_2 from natural gas reforming could be pumped into empty natural gas wells, where available. However, any future CO_2 restrictions will be imposed and enforced by the country in which those emissions occur, which could lead to confusion or inequitable enforcement of credits if new GHGs from the FCV's fuel production occur in a different country (e.g., Qatar) than the GHG savings arising from elimination of ICEV exhaust (e.g., in the US). Therefore CO_2 sequestration, if and when it becomes feasible, may be particularly suited to hydrogen production because that hydrogen will be both produced and consumed in this country. In addition, all of the CO_2 in the hydrogen FCV fuel cycle is emitted off board the vehicle, which allows for sequestration.

4.5.5. Hydrogen FCVs and National Security

What impacts will HFCVs have on oil and gas imports and national fuel security?

Domestic and neighbor-nation natural gas reserves are projected to be ample, given expected exploration and development efforts. As HFCV commercialization spreads and fuel demand rises, additional remote gas resources can be delivered as methanol for direct use in reformers or as LNG for augmentation of the domestic NG supply.

The market penetration of HFCVs, coupled with their substantial fuel economy advantage, can result in a gradual but increasingly substantial reduction in oil imports. To the extent that foreign natural gas is required in later phases of national FCV market expansion, its quantity would be less than the oil displaced, and already-identified remote NG sources are more geographically diverse, closer, and less under cartel control than present oil reserves.

4.6. Public Health and Safety Requirements

Principal public health and safety issues for compressed hydrogen FCVs relate primarily to fuel flammability and explosive potential. The following paragraphs cover the principal issues identified in this study.

4.6.1. Hydrogen Ignition Hazards

How serious are hydrogen ignition hazards with FCVs, and what measures are needed and feasible for providing adequate protection?

Both public and industry concerns over potential hydrogen ignition risks must be acknowledged, even if ill-founded. The 1937 Hindenburg disaster has recently been attributed to the airship's highly flammable exterior fabric rather than its hydrogen tanks (Bain and Van Vorst, 1999). Also, most hydrogen releases, including sudden pressurized vessel failures, result in harmless upward venting to the atmosphere without ignition, and even if ignited tend to simply burn off without further effects. The principal explosive ignition hazard arises from accidental release and entrapment of unpressurized hydrogen in ignitable concentrations in locations where intermittent ignition sources such as light fixtures and motors may be found. Such combinations of circumstances must be avoided.

This study's review of available compressed hydrogen fueling options for FCV introduction led to the view that the initial standard fueling station configuration will involve isolated storage tanks (pressure cascade) designed for fail-safe upward venting, with concrete shield walls protecting adjacent properties. The remainder of the fueling apparatus, including the reformer, fuel cleanup, compressor, and vending devices, are assumed to be connected to the storage tanks by underground piping and integrated into a single factory-built unit for fast and flexible placement to meet site requirements for safe vehicle movement. Development of such integrated units is an essential early task for economic as well as safety reasons.

For hydrogen stored at stations, existing ASME pressure vessel standards apply, requiring various distances between the pressurized tanks and other public facilities for different quantities of fuel stored. The current safety-distance restrictions are significant, and may restrict hydrogen storage and vending to only the largest existing fueling station sites. In order to permit adequate hydrogen storage at a broad range of existing filling stations, including those on smaller urban sites, efforts should begin immediately to assess the safety implications of reduced separation distances and to engage the ASME committee.

For storage and use on the vehicles, the lightweight pressurized composite tanks are subject to US DOT standards. These standards have been updated recently and appear to be satisfactory in their present form. To safeguard against hydrogen ignition on-board, all fuel system failure modes should be identified and design mitigations applied. Potential on-board pressurized hydrogen systems can be designed such that leaks are vented upward and thermal or electrical ignition sources are eliminated.

4.6.2. Invisible Hydrogen Flame Hazards

What measures are required to mitigate possible dangers arising from hydrogen's invisible flame?

Hydrogen's flame is invisible in daylight, with important implications for emergency response personnel dangers and safety procedures. It is anticipated that any hydrogen fire associated with FCVs would quickly ignite other materials that do have visible flames. However, the hydrogen source flame could remain invisible, and there may be other fire sites with no other flammable materials present, such as in the case of a broken valve with high-pressure H2 venting into open air. Current design recommendations include provision of upward venting pathways away from vehicle occupants as well as bystanders, but in collision scenarios this may not provide adequate protection from invisible flame jets.

Because on-board hydrogen quantities are small enough to fully discharge and burn off quickly under pressure, the principal hazard—although with far less personal exposure—may be at fueling sites where larger quantities are stored. The need here is for a collaborative industry effort to address the invisible flame issue for alcohol fuels as well as hydrogen, producing guidelines for incorporation into local emergency response training and procedures.

4.7. Hydrogen FCV Market Development

4.7.1. Consumer Education Challenges

What special consumer education efforts are needed for hydrogen FCVs?

This topic is treated in Chapter 3 for all FCV fuel options. Consumer education efforts unique to hydrogen must focus on broad-based public education on environmental benefits and safety of the fuel itself, on-board the vehicle as well as at stations. Specific issues to be addressed include the inaccuracy of the widely believed Hindenburg dirigible fire story (Bain, 1999) and any imagined relationship of hydrogen FCVs to the hydrogen bomb. Dramatic evidence of safety from fires and explosions will be required.

4.7.2. Unique Product Packaging Needs

Will hydrogen FCVs require any unique product packaging features in order to assure adequate market response?

Chapter 3 includes a discussion of the generic aspects of creating a "package" or "bundle" of FCV features and supporting services sufficiently appealing to attract enough early adopters in the initial market introduction phase. Hydrogen FCVs may require some modification to that packaging concept. Notably, the vehicle configuration may need to be unique in order to accommodate adequate fuel storage for full conventional-vehicle range, or tradeoffs between range and usable space may have to be made, with accompanying marketing rationales.

4.8. Fuel Infrastructure Requirements

4.8.1. Adequacy of Fuel Feedstocks for Hydrogen

Will natural gas and liquid fuel supplies be adequate as FCV numbers grow?

Natural gas supplies are vital to the nation and their continuation will always receive high national priority. At present, exploration for new gas resources is active due to recent price rises, although those prices have fallen substantially from their peaks. Globally, proven natural gas reserves are estimated at 60 years or more of projected use, and even 100 million HFCVs (20% of the vehicle stock in all developed nations) would add only about 2% to projected consumption in 2025. Even domestic supplies are projected to be adequate for years, and in the future liquid natural gas (LNG) can be produced from remote natural gas and imported into the US gas distribution system as necessary.

A more immediate issue for California is the current shortfall in interstate natural gas pipeline capacity. California imports much of its natural gas from the Southwest, Colorado, and Canada, and as of mid-2001 California natural gas consumption was utilizing essentially all available pipeline capacity. In such an environment, adequate natural gas supplies could not be assured for HFCV commercialization. However, both current plans and political pressures for capacity expansion are evidence that, by mid-decade, the state's access to natural gas will be adequate for large-scale FCV use.

Liquid fuels could also be used for off-board hydrogen production. Methanol and gasoline fuel feedstocks should be ample. Ethanol is anticipated to require a mixed-fuel approach. See the parallel sections of Chapters 5, 6, and 7 for details.

4.8.2. Pilot Phase Fueling Technology

What fueling technologies will be most feasible for an early pilot phase?

The early pilot phase hydrogen fueling infrastructure would differ from that to be used in any broader subsequent public introduction phase. During the pilot (fleet) phase, fueling would involve a variety of interim fuel sources, technologies, and subsidies while more refined systems are developed and prepared for widespread commercial use in the market introduction period. The pilot-phase fueling system choices will depend on local site needs and the tradeoffs among investment cost, operating cost, subsidy opportunities, and the value of experimentation. Candidate systems are achievable today, and could include the following:

- Central hydrogen production using primarily natural gas and shipment to stations via CNG tube trailers or LNG cryogenic tanker trucks; station-site storage during this phase can be either in fixed tanks or temporarily parked truck trailers.
- Onsite water electrolyzers and compressors driven by electricity, in some cases possibly linked to an onsite fuel cell unit for distributed generation and combined heat/power production.
- Onsite natural gas and liquid fuel reformers using best-available interim technology, also sometimes possibly linked to a stationary fuel cell to maximize utilization.

The natural gas reformers would be coupled with compressors, gas cleanup devices, and separately located standard ASME pressure vessels. All three options would need to include newly standardized (by then) manual metering and connections to permit self-service refueling. These initial approaches would all deliver hydrogen fuel at above-market costs, and the delivered hydrogen price would need to be kept at or below that of conventional gasoline. This could be done, for example, by any of several limited-term government-backed cost writedown mechanisms to be discussed in the next section. Any such price support would involve very limited fuel volumes and term of use.

These pilot phase fueling facilities would be located at a small number of sites at fleet yards and interim dedicated locations as needed to meet fleet requirements. Where possible, fueling sites would be "outside the fence" and open to all pilot test participants, especially since not all participating fleets will have space for fueling facilities.

4.8.3. Initial Market Reformer-Based Fueling Technology Feasibility

Is there a realistic pathway to the development of a practical near-term mass market hydrogen fueling infrastructure?

Many fueling sites would have to be developed before FCV market introduction, as noted in Chapter 3 for all fuels. Hydrogen poses a special challenge; no cost-effective fueling system exists, although there are many custom-designed and costly units in place for R&D purposes. At least one cost-effective onsite fuel processing and vending technology should be developed and introduced before market introduction begins. Such a system would need to be proven in concept before automakers would be willing to commit to production and sales. This developmental task may require cofunding by the federal government, the State, and/or private investors. The goal for such a system would be to achieve a competitive delivered hydrogen price, or at least a substantially reduced need for introductory subsidy and a clear pathway to cost-competitiveness.

Creative visual and operational design of the public fueling appliance may be used to support marketing efforts by emphasizing ease of refueling and the unique nature of hydrogen FCVs. Also, by the time of HFCV market introduction, at least some jurisdictions and conventional fueling station operators would need to be convinced to allow hydrogen refueling at existing gasoline station sites. Other less crowded options such as shopping center parking lots and inactive former filling station sites could be developed as well.

This integrated technology would include the reformer, fuel cleanup, compression, storage, and vending components. This could be a skid-mounted unit for everything but the storage tanks, which must be isolated. Current technologies could be assembled to serve the early FCV market, but the result would have substantial disadvantages of cost, size, and complexity. The US DOE is already funding early work on an improved and more integrated technology with the principal objective of reducing the cost of delivered hydrogen. Others have proposed advanced concepts for accelerated development (Directed Technologies, 2000), and others will no doubt emerge if compressed hydrogen continues to be seriously considered by automakers.

It will be important for interested automakers to provide clear signals of their intent to potential fueling equipment developers as early as possible, since the effort is anticipated to require several years of development, testing, refinement, production engineering and preparation, and actual production for commercial use in quantity.

4.8.4. Electrolysis Feasibility for Hydrogen Generation

What role can electrolysis technologies play in FCV fueling?

Electrolysis is an attractive option in the early years of FCV market introduction because of its relatively low capital cost, proven performance, and commercial availability. These features could reduce the overall cost and difficulty of providing hydrogen while few vehicles are being served at each station, and the equipment could be moved to newly established locations as hydrogen demand increases at the original sites. Electrolysis is also particularly appropriate for smaller applications such as some fleets and during initial public commercialization because of the difficulty of downscaling reformer-based systems to such low levels.

Electrolyzer technology is well established, but newer PEM approaches continue to be improved and offer long-term possibilities of high-pressure hydrogen delivery without external compression for storage. The PEM electrolyzer technology may also eventually be reversible to operate as a stationary fuel cell for distributed generation purposes, thereby reducing overall costs of operation. This could potentially be a part of the "energy station" concept discussed below. In addition, once renewable electricity sources become dominant as well as much more cost-effective—which is a long-term goal—then electrolysis may play an equally dominant role based both on price and environmental benefits.

The principal concern with electrolyzers during the interim years is their total cost on a per-mile or per-kg H_2 basis. One confidential source indicated that for a moderate-sized unit, including compression, storage, and siting, capital costs could be about $0.08/mile under amortization and interest assumptions that were reasonable except for 100% utilization over the electrolyzer unit's life. Electricity cost based on wind power was estimated at six cents/mile ($0.07/kWh) for a total of $0.14/mile. In the future California market, electricity rates may be somewhat higher (e.g., in the $0.12 range). Current 10-year power purchase contracts are running over seven cents for the generation only, plus five cents or more for distribution. These costs result in a total hydrogen cost of at least twenty cents per mile, or about four times that of current ICEV fuel cost. This cost issue is a serious challenge but is being pursued vigorously by the electrolyzer industry.

The foregoing cost illustration suggests that future decisions concerning hydrogen generator technology must involve a careful cost analysis. At the same time, electrolyzers may prove to be superior in a societal sense because of their potential environmental benefits of relatively low emissions. This is especially true if electrolyzers are clearly linked to specific new 24-hour renewable energy sources. Other benefits include the elimination of many environmental problems of conventional gasoline, including greenhouse gases and local air emissions as well as accidents such as tanker and truck spills, storage tank leaks, and toxic releases, and the resulting health effects as well as the costs and inevitable lapses in enforcement of environmental requirements.

4.8.5. Central Hydrogen Production Feasibility

Is there a role for central production and truck delivery of hydrogen to refueling stations?

Researchers have long noted potential advantages in liquid hydrogen distribution. Compression costs and energy requirements can be virtually eliminated with high-pressure vaporization. Liquid hydrogen is produced from a large-scale central reformer, which would be more efficient than a local reformer. Large-scale facilities can also take advantage of more financially favorable gas contracts, co-production of electric power, and integration of liquefaction with hydrogen purification (and potentially CO_2 sequestration). However, the high-energy requirements of H_2 liquefaction plus the costs of delivery and onsite storage pose major disadvantages.

Studies by Thomas et al (e.g., 1998, 1999c) have indicated that compressed hydrogen fueling stations based on the use of delivered liquid hydrogen could be competitive as well as relatively fast for sites with few vehicles. However, the economics were shown to degrade for larger stations, relative to onsite production. This suggests a possible early transitional role in selected locations near hydrogen production facilities and with low FCV volume.

Central production and truck delivery of compressed hydrogen is already the standard practice for many other uses. As with liquid hydrogen, the costs of delivery and onsite storage combine to make this delivery option less attractive. Central-production concepts were consequently not further evaluated in this study. There may, however, be a transitional role for central production and delivery of compressed hydrogen, as with the liquid form. "Portable" stations with delivered hydrogen, for refueling compressed-hydrogen FCVs, could be deployed quickly and at low capital cost until user volume grows and more permanent onsite facilities can be justified.

4.8.6. Integrated Energy Stations

Can a multi-market "Hydrogen Energy Station" concept be used to reduce FCV hydrogen costs?

The Hydrogen Energy Station concept involves a natural gas or methanol reformer or other hydrogen source feeding both a co-located stationary fuel cell and a hydrogen FCV refueling station. Vehicular demand would be met as needed, and the remaining hydrogen would be used in the fuel cell for distributed-generation sales to the electricity grid, local backup or emergency power, or power quality improvement. The excess thermal energy produced could be used in water or process heating. The result is a single system serving three simultaneous markets and thereby sharing some infrastructure costs among all. Thomas (2000) did a brief analysis of the co-production of hydrogen and electricity for the U.S. Department of Energy, with favorable cost conclusions.

This system could in theory be scaled from a fueling station or commercial-building size down to home or neighborhood scale. At home scale in particular, despite possible efficiency penalties, an electrolyzer might be employed in lieu of the reformer, with slow-fill overnight hydrogen for the family cars plus electricity for the home or grid and water heating for the home as desired. These concepts are clearly worthy of further study and possible technology development, particularly since they may further expand the early market for fuel cells. However, because of the lack of evidence of actual development, this study does not assume their use until after the early FCV market introduction period.

4.8.7. Fueling Station Siting and Construction Challenges

Can the required number of hydrogen fueling stations be designed, permitted, and built without delaying FCV introduction?

This analysis reported in Chapter 3 indicates that the 10-20 small-scale stations required during the fleet pilot phase will cost a maximum of $3 million and probably less. This estimate assumes a lower average station cost than would be required during the later market introduction, because most of these early stations will involve low-volume, lower-cost, temporary installations involving a variety of technologies. These technologies include low-capital LH_2 delivery and electrolysis in addition to early reformer-based prototypes. It is also possible that—in at least some of these pilot phase installations—various refueling technology manufacturers may underwrite some or all of the cost in order to gain experience and visibility. Timely design, permitting, and construction of this small number of stations will be a challenge only because of their novelty and probable custom design. Detailed advance planning and scheduling, use of standard-design temporary or portable systems, and close cooperation with local permitting officials should minimize such problems.

In Chapter 3, a need was argued for at least 500 FCV fueling stations within a few years of market introduction and before reaching an annual California sales level of 40,000 vehicles. If this period is assumed to be 4 years, about 10 completions per month would be required. This is a particular challenge for hydrogen stations due to the complexity of the equipment and installation as well as the potential difficulties and delays of site location and negotiation, design adaptations and permitting, contracting, finding skilled tradespeople, and management of so many separate site projects. However, if the fueling equipment is developed early enough and adequate numbers of well-located and hydrogen-capable station sites can be identified, this task should be manageable—although still logistically demanding—if split among several major fuel vendors. If more detailed study indicates greater problems and a need for more time or more stations, the construction effort must begin one to two years earlier. This would still be well before completion of the pilot phase.

4.9. Fueling Infrastructure Costs, Risks, and Financing

The broad issue of infrastructure financing for all alternative FCV fuels was dealt with in some detail in Chapter 3. However, fueling infrastructure financing is a particularly important issue for HFCVs, due to the relatively high costs involved in making, storing, and delivering compressed hydrogen. Financing needs and sources will differ by phase, and will be facilitated through a variety of approaches.

4.9.1. Upstream Hydrogen Infrastructure Costs

The costs of hydrogen infrastructure upstream of the fueling station appear to present no significant barriers. In the case of liquid fuels, the parallel sections of Chapters 5-7 indicate that incremental costs of sourcing, producing, transporting, and processing can be treated as unit-cost components and are included in the economic analyses of those chapters. For natural gas, the fuel quantities involved are only incremental additions to current urban uses of natural gas. No further infrastructure will be required with the possible exception of location-specific capacity increases in NG distribution piping to fueling station sites. The typical major-street locations of most existing fueling stations are anticipated in most cases to have direct access to high-capacity NG trunk lines and feeders. Further site-specific studies are required to confirm this assumption. The overall cost impact of some NG distribution upgrades will be insignificant in overall system costs if such needs, as assumed here, are not widespread.

4.9.2. Fueling Station Costs

What are the estimated capital costs of hydrogen fueling stations?

This study's assumed standard hydrogen station configuration during at least the first several years of FCV introduction includes an integrated reformer/ cleanup/ storage/ vending system sited at an existing gasoline filling station. An electrolyzer-based alternative could be assumed as well, and others may emerge. A typical early station capacity of 400 vehicles is assumed, or approximately 50 fills per day from a single nozzle at each site. Later additions of nozzles and hydrogen capacity are also included as needed.

As summarized in Exhibit 4-4 and described in the assumptions and analysis of Appendices D and E, these hydrogen stations have assumed average capital costs of $450,000 per station for dedicated single-dispenser vehicle facilities and $300,000 for the vehicular share of integrated "energy stations" that include additional hydrogen generation capacity dedicated to an on-site fuel cell for grid or building power. More accurate estimates will become possible as the required technology evolves and specific site needs become clearer.

Exhibit 4-4: Early-Commercialization Hydrogen Station Cost Assumptions

Capital costs: H_2 station, 50 vehicles/day fueled	$450,000
Energy station (fueling share), same	$300,000
Later added capacity, per dispenser	$220,000

These figures are based on earlier detailed estimates by DTI (Thomas, 1999c) and adjusted upwards based on judgments of the study team and other reviewers. See Appendix D for the Thomas estimates. Even this study's higher estimates, as shown in Exhibit 4-4, are aggressive in their expectation of innovation and cost reductions; costs using current technology would be significantly higher. To achieve the cost levels as assumed in this study, significant technological advances will be required in reformers and electrolyzers, compressors, and overall systems integration as well as mass production methods for that equipment. This study's cost assumptions are based on the time still available for development even under optimistic estimates of FCV market introduction timing.

4.9.3. Delivered Hydrogen Cost Components

What is the assumed delivered cost basis for compressed hydrogen during the FCV introductory period?

This analysis assumes that the per-mile price of hydrogen must be competitive with gasoline. The retail price of hydrogen was fixed on a per-mile basis to be cost-neutral with an assumed price for gasoline as used in a comparable gasoline-electric hybrid ICEV. In this analysis the benchmark for comparison is a gasoline HEV that is 25 percent more efficient than a conventional vehicle, as shown in Exhibit 4-4. While HEVs may be capable of greater fuel economy improvements, there will be a variety of vehicles in the market and there will be sufficient vagueness in the vehicle comparisons for this benchmark fuel economy to be a fair comparison. The assumed efficiency of the HFCV results in a fuel economy of about 33 mi/lb (72 mpeg). If both the HFCV and the gasoline HEV have a fuel cost of 3.1 cents/mile, the HFCV driver would be willing to pay $1.21/lb for fuel.

To derive the "residual" or contribution to capital costs and profit that would be available with this price, assumptions were made for key other cost components unique to each fuel, such as feedstock cost, transportation, and station-related costs. The key assumptions for retail compressed hydrogen are shown in Exhibit 4-5, with further details provided in Appendix E.

In addition, in this example California sales tax but no excise taxes are included for hydrogen. Levying fuel taxes has historically been difficult for CNG, in part because the point of delivery can be anywhere natural gas is distributed. In addition, future taxes on a zero emission fuel may be politically unpopular. With this assumption, the sum of the hydrogen wholesale, retail operations, and sales tax component prices yields an estimated residual of $0.46/lb, which is therefore the amount available to help pay for fueling station costs, maintenance, and financing the capital cost of the station. The final fuel price shown here is $1.21/lb., or $2.64/equivalent gallon of gasoline including taxes.

Exhibit 4-5: Fuel Cell Fuel Cost Parameters–Hydrogen

Parameter	*Value*	*Unit*
Lightweight gasoline ICEV vehicle fuel economy (FE)	45	mpg
Benchmark competition HEV FE	56.25	mpg
Benchmark HEV/ICEV energy efficiency ratio (EER)	1.25	Btu/Btu
FCV EER	1.96	Btu/Btu
FCV FE	40.1	mi/lb
Retail gasoline price	1.70	$/gal

(continued)

Benchmark operating cost	3.0	c/mi
Retail H_2 price target, including sales tax (ICEV-equivalent, based on relative fuel economy)	**1.21/lb**	**$**
/MMBtu natural gas unit price	5.50	$
Natural gas cost	0.48	$
Compression	0.18	$
Wholesale price	0.65	$
Federal tax	-	$
CA excise tax	-	$
CA sales tax	0.09	$
Retail hydrogen residual for capital cost & margin	**0.46**	**$**

Any set of assumptions such as these can be challenged, and should be reviewed carefully. This set, for instance, assumes that either the price of natural gas will retreat from recent very high levels in California (which were due primarily to temporary pipeline capacity constraints and have since abated) or that gas producers will be willing to enter the hydrogen business with a lower allowance for capital cost recovery and margin in order to gain the opportunity to compete for the fuel cell vehicle market. Readers may substitute other values as desired and recalculate cost implications; this study also includes a limited set of sensitivity tests.

4.9.4. Hydrogen Infrastructure Cost Projections

What is the total hydrogen infrastructure capital outlay for the initial California commercialization period?

The results of the financial model developed for this study were found to be extremely sensitive to even moderate changes in key underlying exogenous assumptions. The model demonstrates the net financial implications of the required capital and operating cost investment amounts and timing versus the rates and timing of the revenue stream anticipated for the market development milestones of this study and beyond.

Estimated investment amounts based on the assumptions used are summarized in Exhibit 4-6. These include the straight capital investment, which for the initial 500 stations is 500 x $450,000 = $225 million. In addition, the table shows the total expenditures on station investment and operations through the completion of 500 stations, net of fuel sales revenue. This is a negative total cash flow; its net present value is also shown.

The cost model and its assumptions for this study's results are described in Appendix E. In brief, the model used the same values among fuels for all shared variables such as interest rate, success criterion, and number of stations and vehicles.

Exhibit 4-6: Hydrogen Fueling Infrastructure Investment and Cash Flow

Costs through year 7	*Value ($000)*	
Capital investment	$225,000	(40,000 v/yr)
Net negative cash flow plus capital investment	$234,769	
Net Present Value of cash flow and capital investment	$148,069	

4.9.5. Hydrogen Infrastructure Cost in Context

Is this infrastructure cost reasonable in the context of numbers of vehicles in California?

For perspective, the costs of the early hydrogen FCV fueling infrastructure can be scaled to the fuel costs of the FCV user and the conventional ICEV owner. For the hydrogen refueling station infrastructure in California, this study's estimated $235 million early investment requirement (see Exhibit 4-5) to reach the point of positive cash flow can be viewed in a variety of ways, including the perspectives of FCV users and all California drivers. This is of interest because of the widespread societal benefits that may eventually result from hydrogen FCV use.

If the first decade of FCV owners (i.e., up to when the original infrastructure might begin to need renewal, e.g., ~10 years) had to pay for all of it, the cost could be as much as $300 each, or around $1 per gallon-equivalent throughout that period. This is due to the relatively small number of early FCV users, and is an overwhelming price premium for those users. However, from the perspective of current California gasoline use, now some 14 billion gallons per year, the cost of the initial hydrogen FCV infrastructure amounts to less than two cents per gallon during that ten-year period, i.e., only about $1 per vehicle each year.

4.9.6. Stranded Investment Risks

How great is the risk of stranded hydrogen FCV fuel infrastructure investment?

The risk of stranded investment is significant, since much of an initial compressed hydrogen station infrastructure could not be converted later if either a non-compression hydrogen storage method or a liquid fuel such as a gasoline-ethanol combination proved superior for FCVs. A substantial risk premium may thus be applied by potential hydrogen infrastructure investors, depending on their assessments of this risk based on gasoline and hydrogen FCV technology development and likelihood at the time of the investment decision.

It may be possible to mitigate this risk via insurance or temporary government guarantees. In any case, the market-introduction decision point for automakers and fuel providers will require proof of an acceptable combination of hydrogen technology, economics, and the status of competing fuel alternatives at that time.

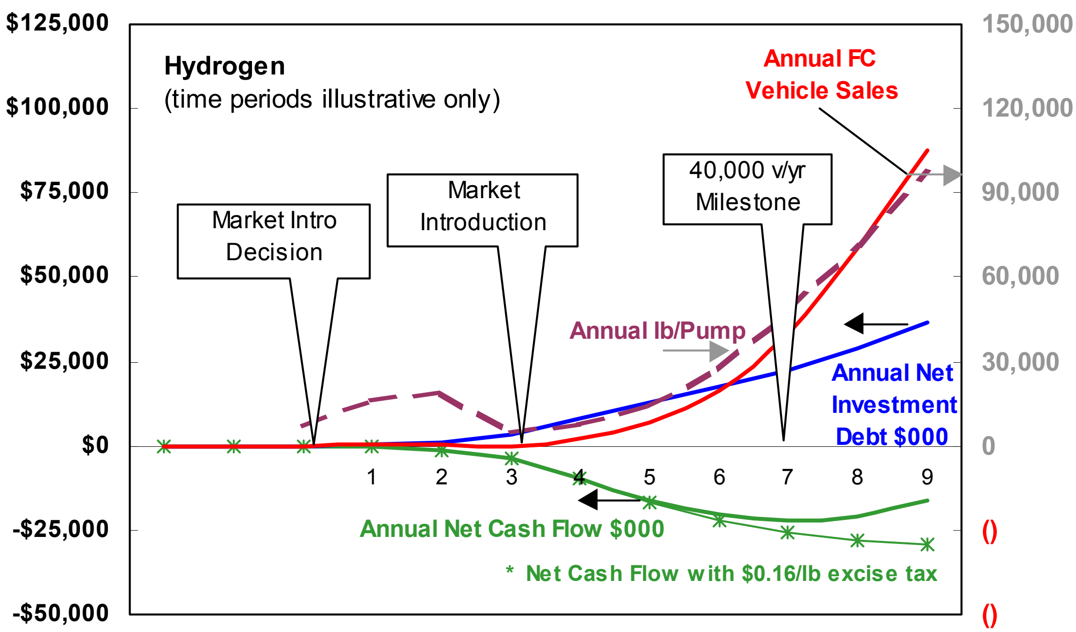
4.9.7. Hydrogen Business Case

Can a reasonable business case be created for investment in hydrogen FCV fueling infrastructure?

Especially since the first-decade hydrogen station investment capital requirement appears relatively large, a strong business case must be made for such a commitment. In this study, for hydrogen as well as all other FCV fuel options, an example business case was developed using a set of cost-factor assumptions leading to **positive infrastructure cash flow within approximately ten years after the market introduction decision**. This is a minimal indicator of future success; the study's cost model can be used to assess other assumptions as well, which could either improve or impair the business case.

The resulting time trend of this analysis is shown graphically in Exhibit 4-7. The line below the horizontal axis represents annual cash expenditures.

Exhibit 4-7: Annual Hydrogen Infrastructure Cost and Revenue Projections



Per this study's success criterion for all fuels, this cash flow line turns positive in approximately ten years from the decision point to invest in full-scale market introduction. This is about eight years after that market introduction occurs and four years after the 40,000 vehicles/year milestone is reached. The "capital investment" line above the axis represents the additional annual investment net of capital payback, and is assumed to be debt that is carried forward. The cash flow line includes interest on that debt, capital payback increments, and all infrastructure costs net of fuel revenue. For any year, the corresponding points on the two lines can be added to yield the total annual funding required.

The investment in infrastructure plus all operating costs net of revenue through the interim period (to year 7, when the 40,000 vehicles/year milestone is assumed to be reached) is some $235 million (about $148 million on a net present value basis). However, if the price of gasoline remains near present levels, local hydrogen production may be an attractive business with reasonable margins. This investment is subject to considerable risk as it hinges on collecting a substantial residual revenue to cover the capital costs. If gasoline prices were to drop, the case for hydrogen would be less attractive. Similarly, if natural gas prices were to rise it would be difficult for hydrogen to achieve price parity with gasoline. Although this business case meets the study's minimum success criterion, the investment magnitudes and risks involved suggest that transitional government assistance may be required to build this initial infrastructure.

Effects of fuel taxes: One governmental assistance mechanism already included in the economic calculations and exhibits for hydrogen is the exclusion of both federal and state excise taxes. Hydrogen is now subject only to California sales tax, resulting in a substantial subsidy relative to other FCV fuels. Hydrogen proponents argue for the continuation of this tax treatment on the basis of its asserted long-term societal benefits and the need for assistance in introducing it into the marketplace.

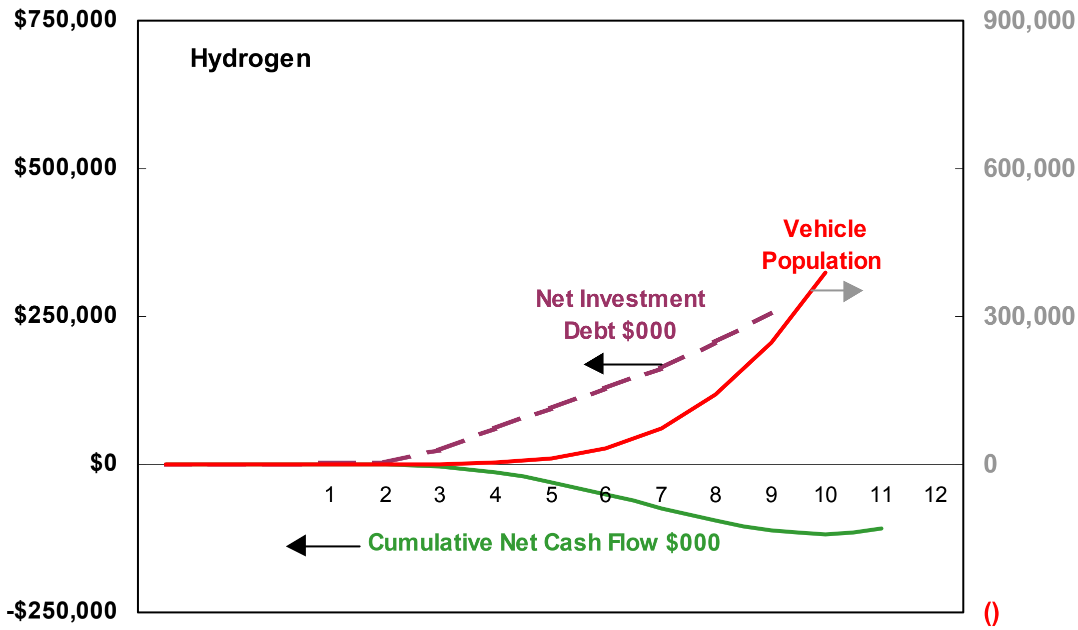
Such governmental assistance appears in fact essential in this calculation. Exhibit 4-7 includes a cumulative negative cash flow line (with a $0.16/lb excise tax) disappearing off the bottom of the graph, showing that a dramatic increase in the amount and duration of negative cash flow would result without this favorable tax treatment during the early years. By year 7 (40,000 v/yr) the effect of the added excise tax results in a cumulative negative cash flow of $241,085, only slightly higher than the untaxed figure, but the annual negative cash flow is still continuing to increase.

This study assumes that the excise tax forgiveness will continue for HFCVs until both market penetration and hydrogen economics reach substantial levels, well beyond the introductory period that is the focus here. Ultimately the lost tax revenue will create a revenue shortfall too great to be ignored, and by that time hydrogen should be expected to be competitive.

Selected cost sensitivities to specific inputs: See Appendix E for a discussion and graph of key cost sensitivities.

Cumulative expenditures and revenue: Exhibit 4-8 is a cumulative version of Exhibit 4-7. This graph indicates that the cumulative cash flow crossover under the cost assumptions used occurs several years later than the annual cash flow crossover. This illustrates the full magnitude of the financial requirements. For further perspective, Appendix E includes a related graph that illustrates the cash flow under a variety of different cost assumptions (for naphtha but similar for all fuels). Reviewers are encouraged to extend this analysis with their own cost rationales and assumptions.

Exhibit 4-8: Cumulative Hydrogen Statistics



4.9.8. Hydrogen Infrastructure Financing Difficulties

How can the required hydrogen infrastructure investment be financed, both initially in California and later throughout the nation?

In the <u>pilot phase</u>, the relatively few site installations needed (10-20) could be financed through some combination of fuel provider investment, fueling equipment manufacturer contributions, and possible federal and state assistance on the basis of the long-term environmental benefits of HFCVs and the need to support the long-term transformation of the automobile market. For optimal collaboration and cost savings, all or most of the refueling sites may be constructed, stocked, and operated by a single provider selected by competitive bidding to an administrative and financing entity which could include government, automakers, and fuel suppliers. The fuel price during this period could also be subsidized by the same entity. Alternatively, several fuel providers may wish to buy into this initial market with low-cost fuel and direct contracts with specific fleets or automakers in order to gain firsthand experience.

In the <u>market introduction</u> period, individual major energy providers may elect to invest directly in expansion of their facilities, possibly including the integrated hydrogen "Energy Station" at some sites. If the financial risks are perceived as too high for single-company sponsorship, the automakers and fuel marketers can use the financial markets to seek other investors and form one or more consortia to share the early market risks and later payoffs. If the business case is judged too risky for this approach, government incentives can be employed if the unique public benefits of the hydrogen approach can be shown. Government incentives to investors, if necessary, can include direct subsidies, stop-loss insurance, or tax credits. Negotiations among potential financial sponsors need to begin two years or more before a pilot phase begins, as do efforts to develop sources and mechanisms for possible temporary fuel infrastructure and retail price support incentives.

Refer to the more detailed discussion of fuel infrastructure financing in Chapter 3 for background. Although ultimately the hydrogen infrastructure must be economically self-sustaining, reliance on some level of government support may also be unavoidable for the first several years of high investment and low numbers of vehicles. Chapter 3 describes some alternative governmental support mechanisms.

4.10. Hydrogen FCV User Costs and Financing

4.10.1. Acceptability of Retail Hydrogen Price

What will be the delivered cost of the fuel relative to the gasoline-equivalent retail price that the user can be expected to pay?

The cost illustrations presented here for hydrogen, as for all other FCV fuels, assume that the fuel must from the outset be priced to be at least cost-competitive with gasoline in comparable hybrid vehicles on a per-mile basis. The delivered price of fuel cell grade hydrogen must therefore be competitive with conventional gasoline on a per-mile basis. Furthermore, the FCV's fuel cost should be compared to high-efficiency hybrid gasoline vehicle models rather than conventional future ICEVs. As shown earlier in this chapter's Exhibit 4-5, this study's economic scenario for hydrogen is based on a retail price of $1.21/lb, or $1.70/gge (gallons of gasoline equivalent). This assumes no hydrogen fuel taxes other than California sales tax. In effect, this means that the cost model results for hydrogen already include a form of governmental assistance relative to conventional fuel tax practices.

4.10.2. Assurance of Hydrogen Price Parity

In the event of low gasoline prices, can hydrogen be kept competitive with gasoline?

Gasoline and natural gas have different natural markets. Particularly in the early years, if gasoline prices were to drop to much lower levels, domestic retail natural gas costs cannot be expected to drop enough to maintain a hydrogen price for FCVs that is competitive with gasoline. Electrolysis may suffer similarly from the then-higher relative price of electricity, which is increasingly based on natural gas. To avoid the resulting unexpected hydrogen price disadvantage, it will be important to have a way to maintain a competitive hydrogen fuel price. As noted in Chapter 3, mechanisms for supporting the price of hydrogen relative to gasoline include long term contracts with gas suppliers that lock in the price to float with the price of gasoline, possibly with government support.

Gas suppliers may be willing to accept the market risk of selling hydrogen despite this uncertainty; however, automakers will want to take steps to assure that vehicle customers are not exposed to significant risk of disparities between gasoline and hydrogen fuel prices. Carmakers can work with fuel providers and government agencies to find mechanisms to assure that their customers pay fuel prices that are consistent with gasoline, as described in Chapter 3.

4.11. HFCV User Support Services

As noted in Chapter 3, FCV user support services include insurance, emergency response, and servicing and repair. Unique elements of HFCV user support may arise from unique hydrogen safety concerns. Although initial auto insurance is expected to be provided for all FCV types without additional cost premiums, both garaging and emergency response services for HFCVs may present unique requirements.

4.11.1. HFCV Garaging Constraints

What special garaging requirements may be imposed for hydrogen FCVs?

HFCVs face some unique garaging issues, but relatively simple solutions can be satisfactory. The prospect of HFCVs has raised some concerns over the possible accumulation of hydrogen near the ceilings of enclosed spaces. This issue is under active study by the industry, including the CaFCP's use of its own FCV maintenance facility in Sacramento as a test bed. Current indications are that relatively minor mitigations such as hydrogen sensors, assurance of positive ventilation, and avoidance of ceiling-area entrapments will be sufficient in enclosed garages and repair facilities.

In parking structures, existing ventilation standards may prove adequate, particularly in structures with open sides. In home garages, a passive above-door vent may suffice. These location-specific questions are expected to be resolved without the creation of costly retrofit requirements, but current efforts in experimentation and standards development should be closely monitored and augmented as necessary to assure timely progress. Any home garaging mitigations required could be included in the FCV sales "package."

4.11.2. Emergency Response Concerns

Are emergency response requirements a significant challenge to hydrogen FCVs?

Local fire officials in locales such as Sacramento, where HFCV prototype vehicles are beginning to be used in public, have begun to address the hydrogen safety issue for emergency response training and operations. As with other earlier alternative fuels, these procedures are typically evolved through training based on known fuel characteristics and field experience. In the case of compressed hydrogen, principal concerns of flame invisibility, lack of radiant heat, and fire suppression difficulty have been handled in a variety of ways. Examples include familiarization of emergency response personnel with these characteristics and the use of responses including the use of straw brooms for fire sourcing and focusing fire suppression efforts on secondary flame sources (e.g., wood, fabric, plastics) and letting the hydrogen burn out rather than attempting direct suppression. These procedures are expected to evolve into standardized codes over the next few years, before any extensive pilot phase or commercialization begins. Such procedures will cover both vehicle and structure fires involving hydrogen, including fueling sites.

4.11.3. Hydrogen Safety Measures

What will be the nature and costs of hydrogen safety measures?

The most needed hydrogen safety measures include public education on the safety aspects, venting standards and enforcement for garages, parking structures and other enclosed spaces, and emergency response personnel training. Public education must be particularly intensive for hydrogen due to popular misconceptions of its dangers that could severely hinder public acceptance. An estimated $50 million (roughly $2 per person) was spent in California on public education concerning the state's original utility deregulation (not to mention the current re-education), and this hydrogen campaign could be equally costly.

Hydrogen venting for enclosed spaces is implied by current hydrogen safety standards, although vehicular applications were not the original intent. An early testing program is needed to provide a basis for review and possible revision of these standards. It is crucial to do so because the potential costs of retrofitting all repair shops, garages, parking structures, and other such spaces could vary from minor to extremely costly depending on the precise requirements established.

4.12. Selected References on Hydrogen FCV Issues

Bain, Addison and Wm. D. Van Vorst, "The Hindenburg tragedy revisited: the fatal flaw found," *International Journal of Hydrogen Energy*, 24 (1999) 399-403.

California Air Resources Board, 2000. Staff Report 2000 Zero Emission Vehicle Program Biennial Review, August 2000.

Directed Technologies, Inc., 2000. Making the Case for Developing Low Cost, Mass Produced Hydrogen Fueling Appliances Fed by Natural Gas, unpublished white paper, January 2000.

Ijaz, Mujeeb I., 2000. Hydrogen Energy Systems in Future Fuel Cell Electric Vehicles, presented at the 17th Electric Vehicle Conference and Exposition, Montreal, July 2000.

James, Brian D., C.E. (Sandy) Thomas, and Franklin D. Lomax, Jr., 1999. *On-board Compressed Hydrogen Storage*, presented at the 9th Canadian Hydrogen Conference, Vancouver, February 1999.

Lovins, Amory B. and Brett D. Williams, 1999. *A Strategy for the Hydrogen Transition,* presented at the 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, Virginia, April 7-9, 1999. http://www.rmi.org/images/other/HC-StrategyHCTrans.pdf

Sopko, Gary M., 2000. *Fuel Cell Demonstration Vehicle "Demo IIa,"* presented at the 17th Electric Vehicle Conference on behalf of TH!NK/Ford Motor Company, Montreal, July 2000.

Thomas, C.E. (Sandy) *et al*, 2000. *Distributed Hydrogen Fueling Systems Analysis*, by Directed Technologies, Inc., for the Hydrogen Program Office (in the Office of Power Technologies), Department of Energy, October 2000 (preprint).

Thomas, C.E. (Sandy) *et al*, 1999a. *Cost Analysis of Stationary Fuel Cell Systems including Hydrogen Co-Generation*, by Directed Technologies, Inc., for the National Renewable Energy Laboratory, December 1999.

Thomas, C.E. (Sandy) *et al*, 1999b. *Hydrogen Infrastructure Report*, by Directed Technologies Inc., Air Products and Chemicals, BOC Gases, The Electrolyser Corporation, Ltd, and Praxair, Inc., for Ford Motor Company.

Thomas, C.E. (Sandy) *et al*, 1999c. *Fuel Infrastructure Costs for Fuel Cell Vehicles*, presented at the 9th Canadian Hydrogen Conference, Vancouver, February 1999.

Thomas, C.E. (Sandy) *et al*, 1999d. *Another Look at the CARB Fuel Cell Technology Advisory Panel Report*, presented at the 9th Canadian Hydrogen Conference, Vancouver, February 1999.

Thomas, C.E. (Sandy) *et al*, 1998. "Affordable Hydrogen Supply Pathways for Fuel Cell Vehicles, " in *International Journal of Hydrogen Energy,* Vol. 23, No. 6, pp. 507-516.

Unnasch, S., 1998. *Evaluation of Fuel Cell Reformer Emissions, Appendix A, Partial Oxidation Fuel Processor Gas Composition and Emission Test Report*, prepared for California Air Resources Board under Contract 95-313, September 1999

Unnasch, S., 1996. *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis*, prepared for California Air Resources Board under Contract A166-134, September 1996.

5 Methanol FCV Challenges and Solutions

5.1. Methanol FCV Overview

Methanol for FCVs has a variety of important advantages. These include the fuel's immediate availability without new upstream infrastructure, high hydrogen-carrying capacity, and ability to be readily stored, delivered, and carried on-board without pressurization. Methanol fueling infrastructure requirements are small, and methanol is also versatile in its ability to support either on-board methanol reformers, station-site reforming into hydrogen for direct hydrogen FCVs, or in eventual direct methanol fuel cell vehicles. Small-scale biomass-to-methanol technology is under development for local use in generating hydrogen for both stationary and vehicular use.

The relative simplicity and anticipated practicality of methanol on-board reformer technology are also critical factors in facilitating early FCV commercialization. Methanol reformer technology is now well along in development, although it has not yet been publicly shown to be reliable, safe, efficient, responsive, and economical enough in mass-production quantities to meet the required ramp-up to this study's initial commercialization volume milestones. However, prototype MFCVs without usable-space compromises are in operation and continued progress toward timely practicality is anticipated.

Offsetting these positive features of methanol FCVs are concerns in both safety and public acceptance arising from the fuel's cosolvency, toxicity, corrosiveness and misleadingly benign color, taste, and flame invisibility. Other concerns include methanol's globally remote principal sources, their long-term pricing and adequate availability for longer-term national or global use, and the economics of methanol infrastructure construction and operation. Opinion is divided on whether future wholesale methanol prices may remain below gasoline or trend upward to uneconomic levels due to future demand growth and market prices for alternative stranded natural gas products such as LNG and GTLs.

The methanol infrastructure cost, principally for modifications to existing fueling station facilities, is substantial. Early investment in methanol infrastructure will carry a risk due to the possible development of a gasoline-fuel alternative, requiring virtually no new infrastructure, not long after methanol FCV introduction. Although methanol tanker trucks, storage tanks and dispensing facilities could be converted to use with alternative FCV liquid fuels, those facilities might not be needed if that fuel were to be conventional gasoline or hydrogen—as predicted by some industry sources. In addition, all new methanol infrastructure would become stranded if later advances in hydrogen storage were to displace an early methanol choice. In contrast, this stranded-investment risk would be relatively small because most of the infrastructure could be adapted if methanol were displaced by either an ethanol fuel or a special non-gasoline petroleum distillate.

With methanol from remote natural gas, the early MFCV's environmental impacts appear to be marginally better than those of future gasoline ICE/ battery hybrid electric vehicles. Other methanol production paths, such as from biomass or local natural gas, appear to be unacceptably costly at least in the early market introduction period. The direct methanol fuel cell, a longer-term MFC variant that may eventually improve MFCV emissions performance as well as efficiency and cost, will be an important later step for improved environmental performance but appears to be far from commercial reality. This methanol FCV assessment presents an approach to resolving such challenges and guiding methanol fuel cell vehicle commercialization to early success in California.

5.2. The Methanol FCV Commercialization Strategy

The Vehicle: The need for timely evolution of the methanol FCV's on-board reformer into a practical state is perhaps the most critical element of the pathway to MFCV commercialization. However, impressive advances have been made recently, including effective sizing and packaging of the reformer on prototype vehicles, and at least one major automaker continues to assert its effective progress toward early introduction. This study necessarily assumes that this technology will continue to be intensively developed to timely market readiness. Other key elements include methanol-specific vehicle market development, which must focus on safety education.

Fuel Pathway: The preferred methanol production and delivery pathway well beyond initial market introduction would almost certainly be from remote natural gas to methanol, ocean shipment to existing California terminals, and truck delivery to existing gasoline fueling stations in the major urban areas. It is also assumed that barge, rail, and truck delivery will suffice for introduction of MFCVs in other parts of the nation. With long-term FCV market growth, it may be necessary to consider dedicated pipelines due to contamination risks in sharing of existing pipelines. Continued efforts are needed to quickly resolve lingering issues of fuel contamination, ingestion, flame invisibility, and cosolvency and spread of existing BTX plumes from locations such as leaking underground gasoline tanks. This requires a more complete analysis of environmental fates, which is now reportedly being undertaken by the methanol industry, as well as the development of practical mitigation plans for any remaining hazards.

Infrastructure Cost and Financing: Fuel-related costs net of revenues through the first few years of commercialization could be financeable primarily by the fuel providers, in anticipation of offsetting gains later, but some limited governmental incentives may be needed. As fueling stations need to be built in advance of large scale vehicle production, fuel providers will need assurances that a vehicle market will develop to match their investment in infrastructure.

5.3. Methanol FCV Challenges and Solutions

The following sections describe the key methanol FCV commercialization challenges that must be addressed, the study team's expectations for the adequacy of current efforts, and recommendations for further solutions judged to be required to assure success. These are organized by topic and challenge as follows in Exhibit 5-1. Specific challenges that proved to be most urgently in need of additional effort are indicated in boldface type. Text sections on each potential challenge follow this table.

Exhibit 5-1: Methanol FCV Commercialization Topics and Challenges

Commercialization Topic	*Potential Challenges*
Vehicle Technology Readiness	Reformer technology readiness Reformer cost implications Fuel contamination of reformer Direct methanol fuel cell technology
Adequacy of Societal Benefits	Air pollutant emissions levels Greenhouse gas emissions effects Multimedia impacts Energy security and diversity
Public Health and Safety Concerns	**Methanol ingestion** Toxicity of additives (if required) Low RVP/fuel tank fire hazards Invisible flame/other flammability concerns Potable water contamination
Fuel Infrastructure Requirements	NG resource availability Other methanol feedstocks Methanol production capacity Transport and distribution Water in fuel Fueling station requirements Construction challenges Longer-term infrastructure expansion

(continued)

Fueling Infrastructure Costs and Financing Requirements	Fueling station costs Delivered fuel costs Infrastructure cost projections Infrastructure costs in context Risks of stranded investment **Business case** **Infrastructure financing**
User Costs and Financing Requirements	Fuel price acceptability Interim financing
Market Development Requirements	Consumer education Product packaging
User Support Services Requirements	Emergency response

5.4. Vehicle Technology

5.4.1. Reformer Technology Readiness

Will methanol reformer technology development delay market introduction?

On-board methanol reformer technology must be proven before the decision point for any phase requiring its use. It must also quickly become economically feasible in order to reach the 40,000 vehicles/year milestone without unacceptably high vehicle costs. That feasibility must be to the satisfaction of the automakers involved, and must also be demonstrated conclusively to prospective methanol fuel providers in order to secure their commitment to invest in the needed infrastructure. If this proves to be impossible, a practical alternative may be for the pilot demo to begin with direct hydrogen FCVs, giving more time for the methanol reformer and fueling infrastructure to be made ready for market introduction. This strategy may be necessary for at least some automakers. Although this topic is beyond this study's scope, timely methanol reformer development success is essential.

5.4.2. Reformer Cost Implications

What are the cost implications of an early methanol reformer price premium?

The methanol reformer technology available by the start of a pilot demonstration phase or even later may not yet be adequately cost-effective for mass market use. However, due to the relatively small volumes of vehicles to be built during the pilot phase, the total excess cost may be reasonable for either government support or manufacturer forward pricing. For example, a $5000 premium on the first 3000 vehicles results in a total premium of $15 million (alternatively, about $600 per year for the life of the vehicle or about $3 per conventional gasoline gallon-equivalent over an assumed 8-year vehicle life at 70 mpg-equivalent). However, if cost-competitive reformers were then to appear and the earlier excess cost amortized over the next 100,000 vehicles, the cost premium per vehicle would be only $150 or less than $20 per year. Alternatively, if allocated to the fuel used by those 100,000 vehicles over an 8-year period, the premium would be about $0.09 per gallon-equivalent.

5.4.3. Fuel Contamination of Reformer

Will fuel additives and contamination be a challenge to reformer success?

Methanol fuel quality control must be assured (see later fuel infrastructure discussion) but is not expected to be a major issue, and reformer performance and life should not be adversely affected by contaminated fuel. The use of additives, however, may be a more serious issue requiring early resolution. It is not known whether additives such as colorants, bitterants, and flame luminosity enhancers will be required for large-scale methanol fuel use. However, the current lack of information on candidate additives and their properties suggests that testing is needed to assess the possibility of contamination of on-board reformer catalysts.

5.4.4. DMFC Implications for Methanol FCV Introduction

Will direct methanol fuel cell technology make a difference in methanol FCV technology introduction?

Here the issue is whether the developing prospects for direct methanol fuel cell technology might serve to delay market introduction of earlier reformer-based methanol FCVs. Direct methanol fuel cells are under development by a variety of sources for both vehicular and stationary uses, and must be considered a serious future FCV option. Small DMFC portable auxiliary power units are reportedly close to market introduction. The DMFC's elimination of the separate reformer should improve efficiency and reduce the complexity, cost, and reliability risks of methanol FCVs. A research-grade DMFC-powered go-cart was recently demonstrated in Japan. However, information gained informally for this study consistently suggested that DMFC technology will not mature to mass production status for standard production autos and trucks until after this decade.

Further intensive development effort is expected for DMFC vehicles, so DMFCVs might be demonstration- and market-ready as early as a few years after reformer-based methanol FCVs. If DMFC advancement continues rapidly during the next few years while other FCV technologies are being readied for a pilot phase, developers might elect to slow the pace toward market introduction with reformer-based MFCVs and other FCV fuel types. However, if the DMFCV proves to be cost-effectively superior, such an early delay could yield a longer-term gain. Even if initial reformer-based MFCVs were to be replaced by DMFCVs, the same methanol fueling infrastructure would then continue to be used when DMFC vehicles appear, so the principal investment risk would be in the reformer and associated vehicle technology. Overall, this challenge is only hypothetical and need not affect present commercialization plans.

5.5. Adequacy of MFCV Societal Benefits

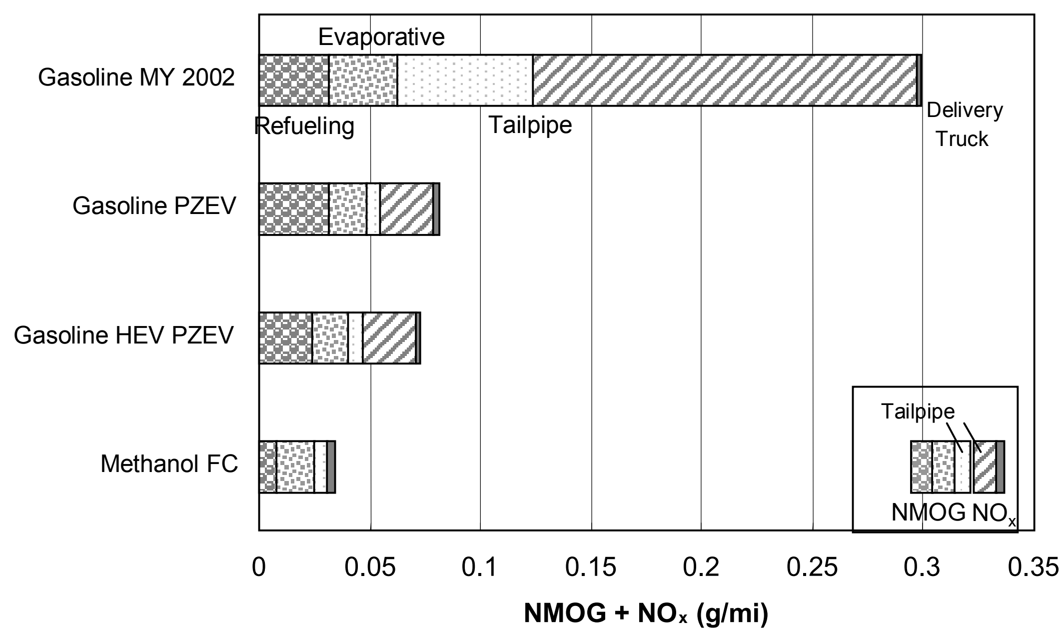
Any methanol FCV technology must demonstrate its contribution to a path toward improved environmental quality in order to justify its costs to the society as well as to its developer, producers, and infrastructure providers. Other societal benefits include national energy security and diversity. This section considers the available evidence of such potential benefits as a basis for public policymaking and investment decisionmaking.

5.5.1. Local Air Pollution Emissions

What are the anticipated air pollutant emissions levels for MFCVs under different fuel source and supply alternatives?

This study's projected local air pollution emissions from methanol vehicle operation are shown in Exhibit 5-2 along with their counterparts for different gasoline baseline vehicles. These emissions include those from the vehicle as well as emissions associated with the delivery of imported fuel to California.

Exhibit 5-2: Estimated Local Air Pollutant Emissions of MFCVs



As indicated in Chapter 3, this marginal-emissions analysis for gasoline alternatives estimates no growth in emissions from added California oil refinery capacity (Hoekman, Unnasch 1996). Methanol would be produced outside California (in fact outside the country) in a remote location presumably without local smog concerns, so the emissions from methanol plants are not considered as local.

Tailpipe emissions are almost completely eliminated in the MFCV. Since the methanol reformer on-board the vehicle operates at 260ºC, the temperature in the reformer burner is too low to produce NO_X. This notion is confirmed by testing from DaimlerChrysler.

Hydrocarbon or NMOG emissions correspond to the small amount of unreacted methanol and formaldehyde emitted from the reformer. These emissions are assumed to be at the level required for PZEVs. Some level of emission control will probably be required to comply with this standard, since these emissions are not inherently zero. The estimates are consistent with modeling estimates for MFCVs (Hoehlein, Unnasch 1998, Dusterwald); however, the estimates do not take into account all the control strategies that are available to carmakers to comply with PZEV standards. MFCVs may provide an intrinsic NMOG reduction if water is condensed from the fuel cell anode. The primary sources of NMOG are methanol and formaldehyde, which are water soluble so could be absorbed in condensate and recycled into the reformer.

Vehicle fueling and evaporative emissions are consistent with those estimated by CARB for PZEV requirements. Refueling emissions are estimated from the vapor pressure of methanol and the amount of fuel that would be spilled from dispensers compliant with CARB rules. CARB also estimates evaporative emissions from the vehicle (seepage through hoses, fuel tank breathing). While PZEVs are required to have fuel tanks with zero evaporative emissions, a small amount of evaporative emissions is still recognized in the emission inventory for PZEVs. These emission estimates largely correspond to an allowance for certification and require further testing once the vehicles are available.

Emissions for comparable gasoline vehicles are also shown. These estimates are consistent with the approach taken by CARB in evaluating its low emission vehicle program (CARB 2000).

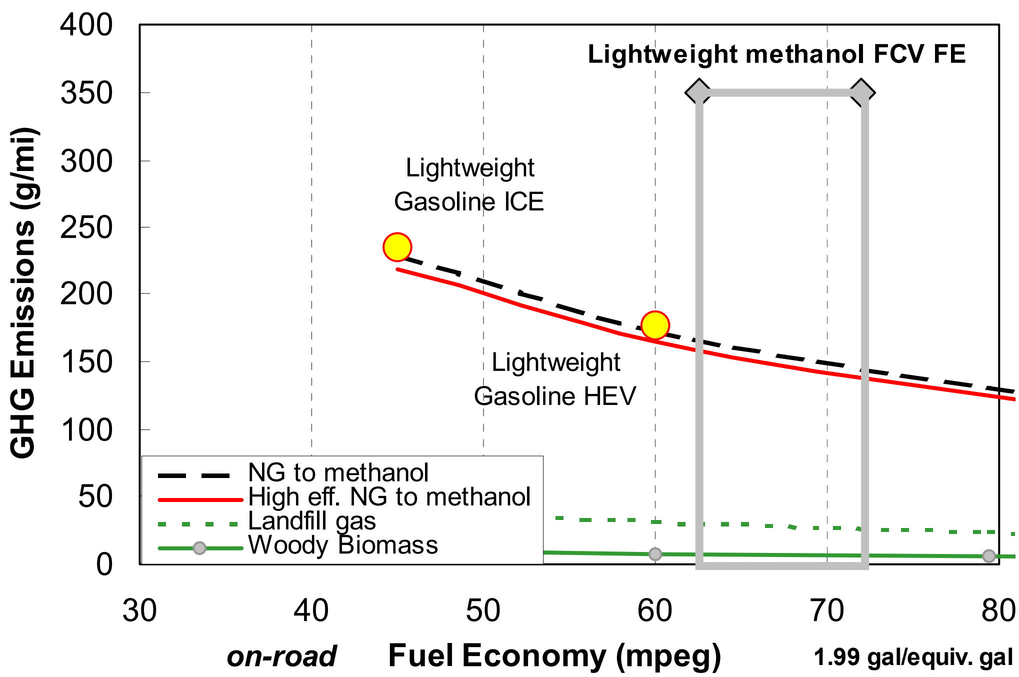
Methanol has one-half the energy density of gasoline, and when taking into account the fuel economy of MFCVs about 50 percent more fuel will be transported. The emissions associated with tanker truck operation have been accounted for. Both methanol and petroleum are delivered to California by tanker ship. Delivering fuel by ship adds to port congestion, and greater tanker ship use for methanol may lead to a higher incidence of ocean fuel spills although this is a small factor and tanker ship technology and practices are improving.

5.5.2. Greenhouse Gas Emissions

What are the greenhouse gas emissions effects of MFCVs under different fuel source and supply options?

The estimated GHG emissions from methanol fuel cell vehicles are shown in Exhibit 5-3. These estimates are derived from our review of existing studies and data, and separate the effects of the fuel supply path from those of the vehicle's fuel economy. The upper curve represents the high range of GHG emissions that are consistent with new methanol plants. The dashed lower curve reflects the GHG emissions associated with a modern integrated facility with an efficiency of 72 percent (HHV basis). In addition, natural gas extraction for methanol production does not require CO_2 removal and subsequent venting as is the case for pipeline gas. All of the CO_2 in the natural gas is fed into the methanol production facility and it has a slight impact on improving the production efficiency (Supp, 1984). Also shown in Exhibit 5-3 is the estimate for landfill gas based production. Landfill gas resources are limited but small scale methanol production facilities have been proposed.

Exhibit 5-3: GHG Emission Rates for Methanol FCV Options vs. Baseline Vehicles



The range of fuel economy estimates is consistent with estimates from carmakers. Some modeling estimates are higher and are not shown on the chart. The value for the methanol vehicles is for an equivalent fuel economy of 63 to 69 mpeg (31 to 35 actual mpg) while the comparably configured lightweight ICEV and HEV achieve fuel economies of 45 and 60 mpg respectively.

These fuel economy values reflect on-road projections for future gasoline vehicles. The comparison was shown with lightweight vehicles (such as those with aluminum intensive bodies and low drag configurations) because these gasoline vehicles achieve the lowest GHG emissions. Furthermore, lightweight vehicle configurations are consistent with efforts under the PNGV program. The rationale for these values is presented in Appendix B.

The reader can use Exhibit 5-3 to assess the effects of other methanol vehicle fuel economy estimates, if desired. GHG emissions from methanol production are affected by fuel production efficiency, as shown in the figure. The efficiency of methanol production and GHG emissions can be improved by using supplemental CO_2 as a feedstock. The lowest GHG emissions would result if residual biomass were gasified to produce methanol or if landfill gas were used as feedstocks. However, the limited available biomass supplies and economics are expected to result in principal use of offshore stranded natural gas for methanol production.

5.5.3. Multimedia Effects

Will methanol have "multimedia" (soil and water) impacts requiring further effort in understanding, regulation, and/or mitigation?

Methanol is water soluble and biodegradeable. These attributes would seem to favor this fuel in terms of both open spills such as from product tank trucks, barges, and tanker ships as well as underground tank leakage. A recent environmental fate and transport analysis for methanol (Malcolm Pirnie, 1999) indicates that open spills in surface water will result in only very localized effects on biota, due to methanol's rapid solubility and oxidation in water as well as its rapid evaporation into air. Methanol was also essentially non-toxic to the fish species tested. However, FCV methanol may require additives for safety, including bitterants, odorants, and colorants, and the environmental effects of those additives were not considered. This remains a topic that should be addressed even if no significant effects are expected.

The same study concludes that the fate of alcohols in some underground leaks requires further study. Alcohols can enhance the mobility of benzene and other gasoline components which could potentially cause an alcohol fuel leak to spread toxic hydrocarbons (BTX) from an existing gasoline leak. This issue was identified more than ten years ago and is being studied by the methanol industry for early resolution.

Leaking gasoline tanks in Lake Tahoe have highlighted the issue of non-gasoline components in underground leaks. MTBE has been found in ground water from leaking gasoline tanks. When MTBE was replaced with ethanol, without repairing the tanks, ethanol also began to appear in ground water. The fate of these oxygenated compounds is being researched by several agencies.

There is some reassuring evidence regarding the environmental impact of methanol, although definitive resolution is still needed. In the late 1980s, a rail car containing methanol spilled in Alaska. The CEC launched an investigation of the environmental consequences and clean-up activities. Based on discussions with investigating regulators, no lasting environmental consequences occurred. Similarly, a 500-bbl methanol spill was reported in Germany involving a burst tank emptying into the Rhine river. By the time investigators could reach the scene, there was apparently no evidence of any effects.

5.5.4. Energy Security and Diversity

As with all FCV fuels options, methanol provides increased vehicular energy efficiency over conventional ICEV and HEV modes and therefore reduced transportation fuel consumption in Btu terms. This in turn reduces Btu energy imports, thus in theory increasing national energy security—although the relatively low energy density of methanol would actually result in an increased *volume* of fuel imports. If produced from remote natural gas, methanol also offers a marginal increase in energy security through its greater dispersion of relatively small remote gas resources in comparison with the nation's current heavy and growing reliance on large foreign petroleum deposits in OPEC nations. Many of the natural gas fields are also somewhat closer to the US, with shorter transportation routes.

Nonetheless, this natural gas is not a domestic resource and is therefore subject to the uncertainties and instabilities of global prices and politics. At the same time, the large-scale introduction of methanol into the nation's energy mix significantly increases fuel diversity, reducing the effects of a possible disruption in price or availability of any one energy source.

Methanol also offers the possibility of alternative domestic feedstock sources if needed, including domestic natural gas, coal gas, and biomass options such as energy crops, landfill gas, municipal wastes, and agricultural wastes. Among these, the biomass options may be key pathways to future sustainable methanol production and major improvements in energy security and diversity. These appear to be major strategic advantages for the longer-term future.

5.6. Public Health and Safety Requirements

Principal fueling system health and safety concerns include methanol ingestion, flammable vapor space creation, flame invisibility, and ingestion of BTX-contaminated water due to methanol release into groundwater previously contaminated by a gasoline spill. Each is discussed in the following paragraphs.

5.6.1. Methanol Ingestion Hazards

Are further measures needed for protection against methanol ingestion?

The principal concern is the acute toxicity of methanol. Methanex has reported statistics averaging 12 methanol-ingestion deaths per year in North America from a public exposure to about 400 million gallons. Most of these fatalities were apparently suicides, which may be at least partially discounted since it is reasonable to assume that persons bent on suicide would find other means if methanol were not available or lethal.

Ingesting 25 to 100 milliliters of methanol is fatal for many people, and lower dose fatalities have been reported. Sub-lethal doses of methanol can cause visual defects including blindness. Ingestion of ethanol soon after the initial methanol ingestion can reduce the risks of methanol poisoning, since ethanol successfully competes for the enzyme responsible for converting methanol to formaldehyde. Another antidote is 4-methylpyrazole, which has been approved by the FDA for treating ethylene glycol poisoning; this compound also inhibits the enzyme that creates formaldehyde, but without the intoxication resulting from the use of ethanol to prevent methanol poisoning.

This high degree of toxicity stands in some contrast to gasoline and ethanol's relatively lesser although still real toxicity dangers. Gasoline produces gastric upset and vomiting--but despite some 30,000 cases annually of emergency treatment for gasoline poisoning (typically due to gas-tank siphoning attempts), deaths are rare.

California's population-weighted share of the 400 million gallon existing annual public exposure to methanol is approximately 50 million gallons. For perspective, this study's near-term FCV commercialization milestone is 40,000 vehicles per year, which results in a total of about 70,000 vehicles on the road at that point; those vehicles would expose the public to an additional 26 million gallons, while at an eventual 25% market penetration this exposure would rise to ~2.6 billion gallons—a 50-fold increase in public exposure.[11]

Due to this greatly increased incidence of public exposure with FCVs, requirements will be self-prescribed by the auto and fuels industries for both physical safeguards (such as nozzle-to-tank seals, fill-pipe check valves, and highly visible warning signs throughout the supply chain) and extensive education and emergency-response training for the general public as well as health and fuels workers prior to and throughout early MFCV introduction. With such measures, the use of additives for public safety might be avoided. This issue should be addressed immediately so that mitigation measures and costs are understood prior to commercialization of MFCVs.

[11] 12,000 mi/yr x 70,000 vehicles / est. 65 mpeg / 1.99 g MeOH/eg = 25,717,000 gal; 25% market penetration in California =~7 million vehicles, or a factor of 100 increase.

5.6.2. Toxicity of Methanol Additives

Will methanol additives, if required, cause further toxicity problems either to humans or the environment?

The danger of methanol poisoning is heightened by methanol's lack of color, odor and taste to deter ingestion. Methanol's toxicity dangers would be greatly mitigated if its taste and odor could be made adequately unpleasant to humans. Although it is not yet known whether additives such as odorants and bitterants will be required for large-scale methanol fuel use, such agents could be effective in very small concentrations (~1-5ppm). The Malcolm Pirnie study identified leading candidate compounds for each function, but concluded that although the required concentrations of each additive are very small, insufficient data are available to evaluate their environmental fate and transport. Further study is reportedly in progress by additive manufacturers and should be followed closely to conclusion and incorporation into an industry standard.

5.6.3. Methanol Fuel Tank Fire Hazards

Will methanol's low RVP result in a need for special measures to protect against fire or explosion arising from a flammable vapor space in fuel storage on-board the vehicle and throughout the supply chain?

Flammable vapor space in storage tanks throughout the methanol supply chain, including on-board the vehicle, is recognized as a possible source of fire or explosion dangers due to methanol's relatively low RVP and broad range of ambient-temperature ignition potential in enclosed spaces compared to conventional gasoline. This is a long-studied phenomenon with much experience and information already collected and a variety of simple mitigations identified such as flame arrestor on tank fill necks and vents, spark-free fuel pumps fuel level sending units, and foam fillers to prevent flame propagation (e.g., Machiele, 1990). Many methanol fueled vehicles (with spark arrestors in fuel tanks, tanker trucks, and storage tanks) have been used for years without recognized need for further mitigations.

Methanol also burns at a much slower rate and has half the energy density of gasoline, rendering such fires less dangerous (US EPA, 1994). Machiele notes that ethanol is also in the flammable range at ambient temperatures but has been used as a transportation fuel in Brazil for many years, apparently without major safety issues. He also reports that limited testing of methanol fuel tanks shows that induced explosions are minor and often contained by the fuel tank with no residual fire.

No further experimental investigations should be needed. The principal further effort now recommended is an industry committee effort to address existing alcohol-fuel ignition mitigation measures and confirm the adequacy of current standard practices.

5.6.4. Other Methanol Fire Hazards

Will methanol's invisible flame and other flammability characteristics require safety measures beyond current standard practice in the methanol community?

Methanol's nearly invisible flame in daylight has important implications for emergency response personnel dangers and safety procedures, and is one of the principal reasons for use of M85 in ICE methanol vehicles today. Any methanol fire associated with FCVs would quickly ignite other materials that do have visible flames, but there may be other fire sites with no other flammable materials present—such as in the case of an open spill on concrete or an ignited leak into air. There is as yet no consensus on whether methanol flame invisibility poses a serious enough danger to require additives, or for the choice of a specific additive, to make the flame more visible. The need here is for a collaborative industry effort to address this issue for both alcohol fuels and hydrogen, in order to produce guidelines for incorporation into local emergency response training and procedures.

Flame invisibility is only one issue within the broader concern of fire safety. Several studies have addressed this concern with similar findings. The US Environmental Protection Agency (Machiele, 1990) noted that methanol fires are much less frequent and serious than gasoline fires, largely due to differences in volatility, lower flammability limit, vapor density, diffusivity in air and other properties which affect the rate of heat generation when burned. Machiele predicted up to a 95% reduction in fatalities, injuries, and property damage with M100 fuel and a 70% reduction with M85 relative to gasoline. In a later bulletin, US EPA (1994) described methanol as much less flammable than gasoline, with fewer fire incidence and less serious fires. In vehicle accidents, US EPA suggests that most fires occur through the rupture of the fuel tank and subsequent ignition in air, which cannot occur as readily with methanol than gasoline. The US EPA also estimates that methanol's use should reduce injuries, deaths and damage due to fires in the fuel distribution system. A separate study by US DOE (1991) briefly reviewed and confirmed the US EPA's overall view of relative methanol fire safety.

5.6.5. Soil and Groundwater Contamination

Do risks of groundwater contamination or soil oxygen depletion due to methanol require further study or mitigation?

Ingestion of methanol-caused BTX contamination of water has been suggested as a possible methanol fuel danger. The hypothesized mode of contamination would be a methanol spill percolating into a static or very slow-moving residual plume of toxic benzene, toluene, and xylene (BTX) from a prior underground gasoline spill. Until the introduction of the methanol, the BTX plume's migration is restrained by its gradual degradation by microbes encountered in the soil. The later-introduced methanol would then be preferentially degraded by the microbes, allowing the BTX to survive longer, possibly reach the water table, and from there migrate to wells or other outlets. The methanol itself degrades and disperses rapidly with no toxic effects. However, the BTX toxics could exacerbate already-confirmed serious health dangers to water sources. This topic requires further experimental research soon on the degree of danger and risks of exposure, and reportedly this work is being undertaken by the methanol industry.

It has been suggested informally within the CaFCP that methanol's rapid decomposition in an underground spill might reduce oxygen levels in the soil to levels dangerous to local biota. This is also mentioned as a possibility in the Malcolm Pirnie study, but the effects are anticipated to be so transitory and limited in size, as well as uncommon, that no major concern is anticipated. However, this issue should be pursued and resolved through experimentation.

5.7. Methanol FCV Market Development

5.7.1. Consumer Education Needs

What special consumer education efforts are needed for methanol?

Consumer education efforts unique to methanol must focus on broad-based public education on the safety of the fuel itself, both in the infrastructure "pipeline" and on-board the vehicle. This is part of a positive campaign positioning methanol--as with any other FCV fuel--as "the fuel of the future." In addition to safety, the conveniences and environmental benefits of methanol FCVs should be stressed through a cooperative media program. Such a program might be jointly supported by government and industry.

Such a methanol education program should begin at least a year before the start of the pilot phase. It should focus first on fleet users in preparation for the pilot test phase. Due to the inevitable national media attention by that time, a broader public-targeted campaign will also be needed nearly as early, including a strong focus on educating media personnel and other opinion leaders. That campaign will continue until at least a year after FCV market introduction, alternating with periodic panel-type market research to gauge the development of public attitudes toward MFCVs.

5.7.2. Unique Product Packaging Requirements

Will methanol FCVs require any unique product packaging features in order to assure adequate market response?

Chapter 3 presents a discussion of the generic aspects of creating a "bundle" of FCV features and supporting services sufficiently appealing to attract enough early adopters to reach the 40,000 v/yr milestone. This is a major issue for all FCVs. However, methanol FCVs require no modification to that packaging concept other than to focus the early educational efforts on the safety and convenience of methanol fuel.

5.8. Fuel Infrastructure Requirements

5.8.1. Adequacy of Natural Gas Feedstock Supply

Will enough low-cost natural gas be available to meet FCV market scenarios?

Fuel feedstock sources for methanol FCVs appear to be adequate in the near term, in the form of remote natural gas available from various foreign fields in large quantities at low cost. The estimated 2025 FCV population (estimated at 90-100 million vehicles) would add less than 2% to the world's projected natural gas usage in that year. Proven recoverable natural gas reserves worldwide now stand at over 5,000 trillion cubic feet, roughly a 60-65 year supply. For the quantities needed for FCVs, enough of all untapped natural gas reserves can be assumed to be in remote locations suitable for methanol production.

In addition, much more remote natural gas is still untapped and more remains to be discovered. The American Methanol Institute (1999) notes that proven worldwide natural gas reserves are estimated at 60 years or more of projected use, and even 100 million MFCVs (20% of the vehicle stock in all developed nations) would add only about 2% to projected consumption in 2025.

In the FCV market, in this study it is assumed that methanol must be available at retail prices competitive with gasoline for ICEVs and HEVs on a per-mile basis, since potential FCV makers as well as users will naturally resist the concept of a price premium for fuel. In such a market, a key concern is future methanol price parity with gasoline and whether producers will choose to produce it rather than a competing product such as LNG or GTL fuels for other markets. Some observers predict competition among such products for the available remote natural gas feedstocks, which could raise the cost of methanol production above current predictions. See Appendix I for this study's methanol price forecast assessment.

That competitive scenario predicts rising demand and price for LNG, because of the high price of US gas, and similarly for GTLs such as synthetic diesel, due to its sulfur-free quality for use in meeting future diesel emissions regulations in the US and elsewhere. This could occur, however, only if methanol, LNG, and GTL production competed for the same remote gas resources. In that case the NG feedstock cost would rise for methanol, resulting in lower margins unless its consumer prices (including those for FCVs) could be increased…which would be undesirable for FCV makers and users. Even without such feedstock competition among synthetic fuels, the methanol FCV user would be a captive methanol user, and the only competitive methanol price pressures would be those imposed by competing methanol producer-wholesalers.

The opposing position is that the huge quantity and diversity of remote natural gas resources could accommodate all competing fuel product quantity requirements for many years without direct price competition. LNG and GTL producers tend to focus their efforts on the larger remote NG fields in order to support the very high capital cost of competitive-scale plants (e.g., $1 billion for LNG). Methanol producers will see unique value in developing less costly methanol capacity in the many smaller fields available worldwide. This is due to several factors, such as methanol's smaller-scale economics (although "smaller" in LNG terms is actually still a very large methanol plant, e.g., 2500-5000 tpd), its intrinsically lower cost of production, and its profit potential in specialty markets—which in the future could add FCVs. This position is based on current forecasts and offers of low methanol feedstock (NG) prices over the next 30 years, and counters the view of an upward price pressure on methanol producers. The same observers argue that competition among methanol producers for the FCV market would indeed serve as an effective restraint on artificial fuel price increases outpacing gasoline, particularly in view of the likelihood of long term upward pressures on gasoline due to rising worldwide demand.

5.8.2. Availability of Alternative Methanol Feedstocks

Will methanol FCVs have to depend solely on remote natural gas feedstocks?

Remote natural gas is the most economically attractive feedstock for methanol, but there are others which could help to provide fuel flexibility. Methanol is the most cost-effective alcohol product of biomass distillation, although this study's review of this evolving process and its possible implementation trajectory for California and the US at large suggests that biomass could represent only a small source for methanol either in this decade or later. Its production costs are uncertain and may not permit competitive fuel prices. In addition, during this decade, at least, the recent trend toward replacement of MTBE by biomass-derived ethanol for gasoline oxygenation purposes must be acknowledged. This rapidly increasing mandated ethanol demand—which in California alone will overwhelm in-state biomass resources that might otherwise be used for methanol production—will stretch the limits of available and economic biomass resources nationally unless new techniques emerge to make effective use of a broader range of biomass streams including agricultural and municipal wastes.

However, new technologies are in development for biomass-to-methanol use with FCVs: Schwarze Pumpe GmbH in Germany is reportedly developing a small scale process for conversion of selected municipal wastes into methanol for combined use in co-located stationary fuel cells and FCV fueling sites. Methanol could also be produced from domestic natural gas--and in theory at least, this could be done at reduced scale at the vehicle refueling sites. However, the current and forecast high costs of the domestic natural gas feedstock option plus the small-scale conversion process appear to render these options impractical in most situations–but further technical developments could reverse this conclusion.

Other possible domestic sources for methanol include coal gasification and coalbed methane, both of which are available in potentially commercial-scale quantities. Process difficulties and cost currently appear to make these sources uneconomic. Also, the adequacy of remote natural gas resources appears to make these alternative sources of methanol unnecessary, although they could be developed later if global fuel prices and availability were to change drastically.

5.8.3. Adequacy of Methanol Production Capacity

Will enough methanol fuel be available for FCV use nationwide and beyond?

The longer-term future envisions far greater methanol FCV use both within and beyond the California market. Gradual growth to 25% of light duty vehicle sales throughout the developed world (perhaps by 2025 or so) would yield a total FCV population of about 90-100 million vehicles. This would also be about 20% of the total light-duty vehicle stock in those countries. This number of vehicles would require about ten times the excess methanol production capacity now available (and three times today's *total* methanol production capacity). However, methanol plants can be built in 2 to 3 years as demand grows.

Some 10 million tonnes/year of unused methanol production capacity (25%) is available in locations worldwide such as Saudi Arabia, Venezuela, Canada and Trinidad. This production capacity is enough for approximately 10 million FCVs. In contrast, this study estimates only approximately 175,000 FCVs in use in California by the time the 100,000 vehicles/year milestone is reached. This number could expand possibly to as high as 500,000 by the time the 100,000-vehicle California milestone is reached if intensive national and worldwide FCV commercialization were begun soon after the California market introduction.

While current excess methanol production plant capacity may not be technologically or economically viable if left unused until needed for MFCVs, larger methanol plants (approaching 5000 tpd) with lower production costs are already supplanting the older small units despite soft worldwide demand for methanol. FCV fuel represents an important new potential global market for that renewed excess capacity.

By about 2025, a transition to methanol FCV fueling from renewable energy sources might be well underway, and could gradually phase out refueling with methanol from conventional sources. In addition, other currently uneconomic natural gas deposits are collectively estimated to be far greater than all other types of fossil fuel reserves, including natural gas. These future sources include coal, coalbed methane (as noted earlier) and notably undersea methane hydrates.

5.8.4. Methanol Transport Difficulties

What are the estimated requirements and costs for the long-distance transport and distribution of methanol?

Methanol is known to cause deterioration of aluminum and some elastomers commonly used in seals and pipe fittings for gasoline transport, so special modifications to transport facilities are routinely required. Fuel transport and delivery for remotely produced FCV methanol well beyond this study's 40,000 vehicles/year milestone will involve ocean and truck shipment for which existing technology is satisfactory and capacity available.

Existing ocean shipment is via dedicated barge or tanker ship, with capacities of 45,000-100,000 dwt. Trans-shipment and delivery from ocean and waterway terminals uses dedicated tank trucks. Methanol is already imported and land-shipped using these methods, and the FCV fuel volumes required during the early FCV introduction phase would represent only small additions to present import levels. Since state-level data were not available, this study's analysis assumes a similar per-capita use of methanol among states: MFCVs at the point of 40,000 vehicles per year in sales would increase estimated California consumption for other purposes by only about 15%. California is also a methanol import and transshipment point for some Western inland areas, so the increment to present California throughput would be an even smaller percentage.

This study's cost analysis addresses the transport issue for methanol through per-gallon cost increments for both ocean shipment and truck delivery. This allows incremental transport capacity to be funded as needed. These levels of transportation services are very low: Even for the basic 40,000-vehicle target, the quantity of methanol involved for the year is less than one shipload and delivery among the 500 stations requires about three tanker trucks and one visit to the average station about every two months.

Longer-term MFCV use in areas of the country using terminals not accessible by fuel barges appears to require a dedicated methanol pipeline system, based on informal industry views encountered in this study. This will necessitate reliance on long-haul tanker trucks in those regions, marginally increasing methanol fuel cost. Dedicated pipeline shipment to inland terminals can be made available using known technology, when methanol demand rises enough to amortize its costs. Such a future shift from long-haul truck shipment to pipeline delivery to landlocked terminals will require a thorough cost recovery assessment based on then-current fuel usage volumes, market projections, and the likelihood and timing of possible later displacement of methanol by hydrogen or some other fuel.

Prior experience with methanol vehicle field demonstrations has shown a significant risk of in-transit contamination with other products such as gasoline or diesel fuel. While procedures exist to assure pure methanol transport and eliminate contamination, the California experience with earlier methanol fuels demonstrates that such procedures are subject to human error. Therefore for the fuel cell system, which has stringent purity requirements, more careful attention to the integrity of the supply chain will be needed. This study's cost model includes a small additional cost for this purpose, although methanol industry representatives assert that the existing procedures are already adequate.

5.8.5. Assurance of Methanol Purity

Will methanol contamination by water be a problem?

In the existing wholesale methanol distribution system this problem is apparently managed well. The standard delivery specification is max 0.15% water; actual levels are reportedly much lower. Costs are minimal and already included in the current price structure. Methanol's miscibility in water is a benefit for fuel cell vehicle operation in cold climates. The methanol can be added automatically to the small amount of water required on-board FCVs to keep the fuel cell membranes hydrated at startup without concerns of freezing. Nonetheless, procedures for assurance of known levels of water in methanol fuel will be needed to guarantee the energy value of the fuel for the consumer.

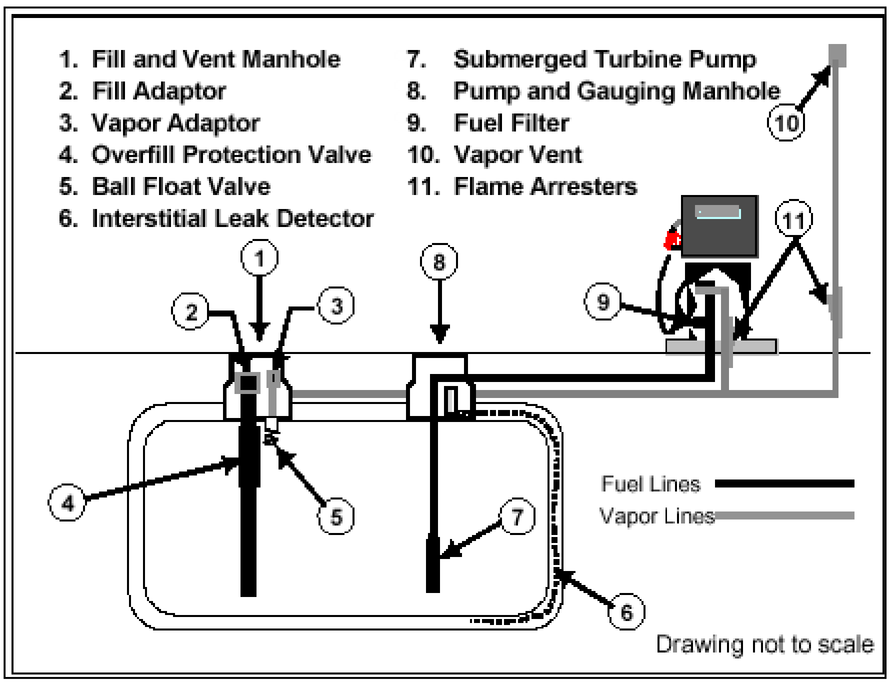
5.8.6. Fueling Station Requirements

What are the physical requirements for methanol fueling stations?

Fueling stations could be developed either by modification of existing gasoline outlets to add methanol or the construction of new methanol stations if and as needed. The legitimate concerns of current gasoline fueling station owners about methanol-related safety, liability, and cost issues must be recognized, as attempted in this study. However, those existing fuel marketers are also reluctant to yield the methanol retail market to others, and the emerging development of solutions to such concerns appears to be contributing to an increasing openness to methanol in existing gasoline stations. If this apparent trend continues, few if any all-new methanol stations may be needed.

Typically the addition of methanol vending capability will involve the addition of pumps and either a new underground tank or the conversion of an existing tank from gasoline to methanol. Exhibit 5-4 shows typical methanol fueling station requirements.

Exhibit 5-4: Schematic of Methanol Fueling Station



(Source: EA Engineering, 1999)

A recent independent cost study ((S&T)^2 Consultants, Inc.) estimates that existing tanks can be converted economically for methanol by cleaning or relining and re-piping in place. Many existing tanks are already methanol-compatible and require only cleaning and re-piping due to California requirements imposed in the statewide tank replacement program in the 1980s. However, if gasoline revenue is not to be lost, the conversion of an existing tank at most stations would require either the elimination of the mid-grade gasoline option or its onsite blending from the premium and standard grades using new piping, dispensing, and metering equipment. Two-tank blending for mid-grade gasoline is reportedly already a common practice in California, so for those stations a new tank will be the only option for methanol.

5.8.7. Initial Infrastructure Construction Challenges

Can enough stations be modified for methanol without a major delay in FCV market introduction?

As noted for all fuels in Chapter 3, modification of 500 existing stations in 4 years would need to occur at a constant rate in order to provide minimally acceptable access to fuel for the early public-market FCV users. Front-loading of the station population is unnecessary, since marketing selectivity can be used to control both where the initial vehicles are sold and the needs of their earliest adopters. 125 stations per year, or about 10 completions per month, represent substantial but not overwhelming construction and management tasks, particularly since several major fuel providers will be involved.

This rate of tank replacement and station upgrading is similar to or less than that observed during the recent years of required underground tank upgrading for some 10,000 stations throughout California. In addition, the construction effort, special materials, and skilled labor required for this methanol addition is not materially different from that needed for the gasoline tank upgrading. EA Engineering estimated the typical station project at 10 days for a tank replacement and much less for tank relining or cleaning. Allowing for special site needs and normal scheduling delays, actual construction time could be as much as a month on average, so about 12 sites could be under construction at once plus several times as many in various stages of design and permitting. Still, due to efficiencies of scale and standardization the average pre-construction effort on each site would be low. This leads to the conclusion that this task is manageable, particularly if split among several major fuel vendors.

5.8.8. Long-Term Infrastructure Development Challenges

Do longer-term national implications of methanol infrastructure construction present other challenges?

Within a few years after reaching the 40,000 vehicle/year milestone, it must be assumed that a similar level of FCV infrastructure will be needed in other states as well as Europe, Japan, and elsewhere. For purposes of estimation, the California schedule scenario can be replicated over a 10-year period to reach similar market penetration nationwide. Since California's retail fueling stations represent approximately 10% of the national total, nationwide sales or support for FCVs will require methanol capability in at least 5,000 stations and probably much higher by the end of that first-stage transition—and still increasing for some years afterward. This is a much greater challenge and cost than estimated for California alone, and will tend to slow the feasible pace of FCV introduction. This challenge is multiplied if the California introduction requires governmental incentives that must be replicated in every other state.

5.9. Methanol Infrastructure Costs and Financing

As with all fuels in this study, the principal objective here is to provide an estimate of the infrastructure costs during the critical transitional years when methanol would be just entering the market with FCVs. A secondary but important objective is to indicate the assumptions on which that cost estimate is based. Particularly in view of the hazards inherent in predicting variables such as future fuel prices, construction, costs, numbers of stations needed, and market response, it is important that users of the study have the information needed to estimate the effects of changing those assumptions. This section, along with Appendix E, presents that information plus some sensitivity tests on selected variables.

5.9.1. Fueling Station Costs

How high are the estimated costs for methanol fueling stations?

In this study the EA Engineering cost estimates were adapted to allow for several additional project elements including project management, administrative overhead, adjustment to year 2000 cost base, and a variety of special requirements at individual sites. Such special needs may include shoring, dewatering, installation close to other tanks, underground remediation, poor access, vehicle barriers, lighting and other electrical upgrades, and special island extensions or decorative treatments. In this study a 20% allowance is added for the special site requirements and the management, administrative, and base-year adjustment costs are assumed to be 5% of all direct costs. This results in the following cost estimates of Exhibit 5-5, which apply to ethanol and naphtha fuels as well.

To average these costs, and in the absence of data on specific station needs, this analysis assumes that about 75%% of all stations will require new tanks for methanol. This is due to the reported present use of only two tanks with mid-grade gasoline blending at many stations. This results in an average estimated additional cost of some $70,000 per station to add methanol fueling capability. In addition, it is assumed that later incremental upgrades to stations including an additional pump, piping, associated island modifications, and any interim necessary upgrading of existing equipment would average $28,800 in further costs as shown. Such costs would not be anticipated until at least five years after initial installation.

Exhibit 5-5: Methanol Fueling Station Cost Estimates

	New tank	*Upgraded tank*	*Later pump adds*
EA Engineering estimate	$62,400	$31,000	$19,200
20% allowance for site-specific requirements	$12,500	$6,200	$3,800
25% factor for admin & management costs	$18,700	$9,300	$5,800
Total estimated costs	$93,600	$46,500	$28,800

For the minimum estimated 500 stations needed for FCV market introduction in California (see Chapter 3 for further details on the number of stations needed), the total estimated station investment is thus approximately $35 million if staged over a 4-5 year period. This number of stations would continue to rise beyond this level, to an ultimate population that will be determined through user response—but as for other FCV fuels, anticipated to be in the range of 15-25% of the state's existing ~9500 retail auto refueling stations. This means that the infrastructure investment will continue indefinitely, as it now does for gasoline station construction, replacement, and upgrading.

5.9.2. Delivered Methanol Cost Components

What is the assumed delivered cost basis for methanol fuel during the FCV introductory period?

This study's analysis of methanol fuel cost and pricing was built on estimates of key cost components. Appendix I presents a review of methanol pricing factors and expectations, leading to an estimated wholesale price estimate for the FCV introductory period. Adding transport costs yields a wholesale price to the terminal, and various taxes, terminal costs, and truck transport are added. The amount available for coverage of the remaining infrastructure costs, including capital recovery, is then derived by deducting those cost components from the "target" fuel unit price, which is the methanol equivalent of the per-gallon gasoline price for a comparable ICEV. This results in retail fuel price parity.

The study's illustrative estimates of fuel-equivalence assumptions and methanol cost components are shown in Figure 5-6.

Exhibit 5-6: Fuel Cell Fuel Cost Parameters–Methanol

Parameter	*Value*	*Unit*
Gasoline subcompact fuel efficiency (FE)	45	mpg
Benchmark Competition HEV	56.25	mpg
Benchmark HEV EER	1.25	Btu/Btu
FCV EER relative to gasoline	1.5	Btu/Btu
FCV FE	33.9	mpg MeOH
Retail Gasoline	$1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Retail Methanol Price Target, w/tax (ICEV-equivalent, based on relative fuel economy)	**1.03/gal**	**$**
Bulk fuel cost	0.38/lb	$
Bulk fuel margin	0.15	$
Bulk fuel transport	0.05	$
Wholesale price (sum of above three items)	0.58	$
CA sales tax on target retail price	0.06	$
Bulk fuel storage terminal	0.02	$
Truck transport	0.05	$
Federal tax	0.09	$
CA excise tax	0.09	$
Derived residual to cover capital costs & return	**0.13**	**$**

5.9.3. Methanol Infrastructure Cost Projections

What is the total capital outlay for the initial California commercialization period?

As with other FCV fuels, a complete infrastructure financial analysis must include not only the capital investment but also the share of the methanol fueling station operating costs attributable to the FCVs. This includes a share of the station's total fixed costs plus variable costs attributable to FCVs such as fuel purchases, equipment maintenance, repairs, and additional electricity requirements. The retail fuel revenue stream can then be compared with this combination of capital and operating costs over time to assess factors such as net cost recovery and return on overall investment. Exhibit 5-7 presents the resulting total expenditures through the year of 40,000 vehicles per year sales rate (here assumed for illustrative purposes as year 7, or the fourth year following FCV market introduction).

Exhibit 5-7: Methanol Fueling Station Costs

Costs through year 7	*Value*	
Capital investment	$35,000	(40,000 v/yr)
Net negative cash flow plus capital investment	$57,918	
Net Present Value	$36,967	

5.9.4. Fueling Infrastructure Costs in Context

What are the costs of the methanol FCV fueling infrastructure relative to the fuel costs of the FCV user and the conventional ICEV owner?

For the methanol refueling station infrastructure, the estimated $58 million investment requirement by the time of the 40,000 vehicles/year milestone can be viewed in a variety of ways, including the perspectives of FCV users and all California drivers. This is of interest because of the widespread societal benefits that may result from FCV use.

If the first decade of FCV owners (i.e., when the original infrastructure might begin to need renewal—several years beyond the 40,000 vehicles/year milestone, with an assumed 1 million FCVs sold in California by that point) had to pay for all of that initial infrastructure cash-flow loss, the cost would be about $60 each, or around 35 cents per gallon throughout that period…a significant price premium. However, from the perspective of current California gasoline use, now some 14 billion gallons per year, the cost of the initial MFCV infrastructure amounts to less than one-half cent per gallon for one year…or about two dollars per car, one time only.

5.9.5. Stranded Investment Risk

How great is the risk of stranded MFCV fuel infrastructure investment?

The risk of stranded investment would be low if most of the new methanol station infrastructure could be converted later to meet the needs of either a non-gasoline petroleum derivative or ethanol successor fuel for FCVs or alternative-fuel ICEVs. However, if methanol were to be supplanted by conventional gasoline for FCVs, much of the separate methanol infrastructure would be surplus to the gasoline requirement and therefore a stranded cost. Similarly, replacement by hydrogen would not make use of the former methanol infrastructure due to its very different needs. A risk premium may thus be applied by potential methanol infrastructure investors, depending on their assessments of this risk based on gasoline and hydrogen FCV technology development and likelihood at the time of the investment decision.

5.9.6. Methanol Infrastructure Business Case

What is the overall financial outlook for investment in MFCV fuel infrastructure?

This study's analysis modeled the financial implications of the required capital and operating cost investment amounts and timing, continuing beyond the 40,000 vehicles/year milestone, versus the rates and timing of the revenue stream anticipated for the market development scenarios of this study and their extension well past that point. This cost model and its assumptions are described in Appendix E.

For methanol, the results of this analysis are shown in Exhibit 5-8 (next page). For this study's assumptions and analysis approach, these results indicate that the study's success criterion is met: Without subsidy the annual net negative cash flow for the fueling stations will turn positive about 10 years after introduction, or 4-5 years after reaching the 40,000 vehicles/year milestone.

Cumulative vehicles and costs are shown in Exhibit 5-9, illustrating the longer time required for full recovery of prior negative cash flows.

Exhibit 5-8: Methanol Fueling Infrastructure Cost and Revenue Projections

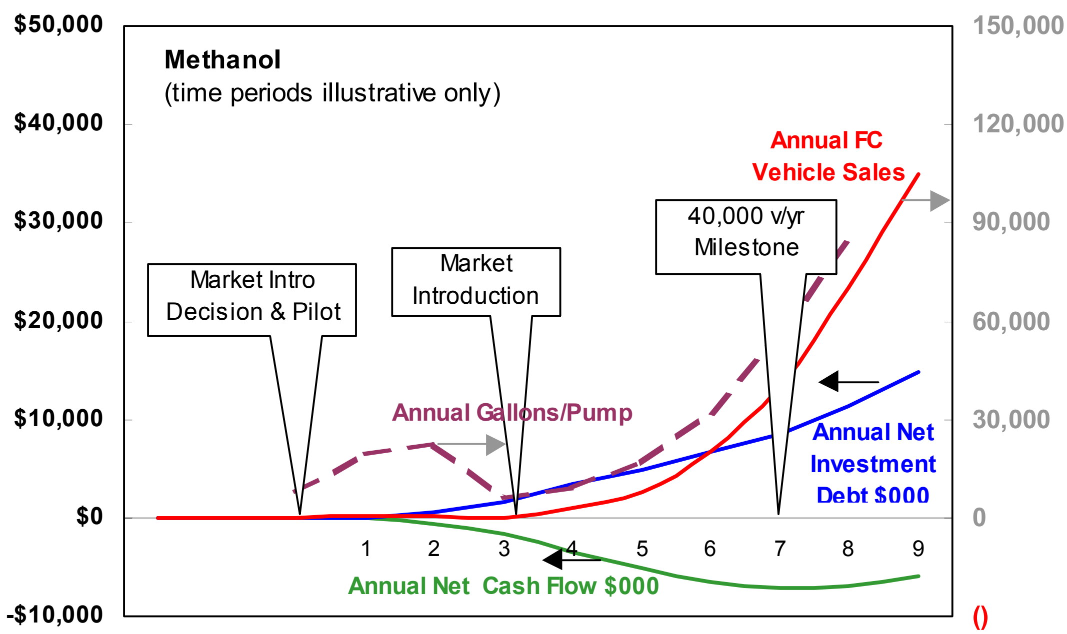
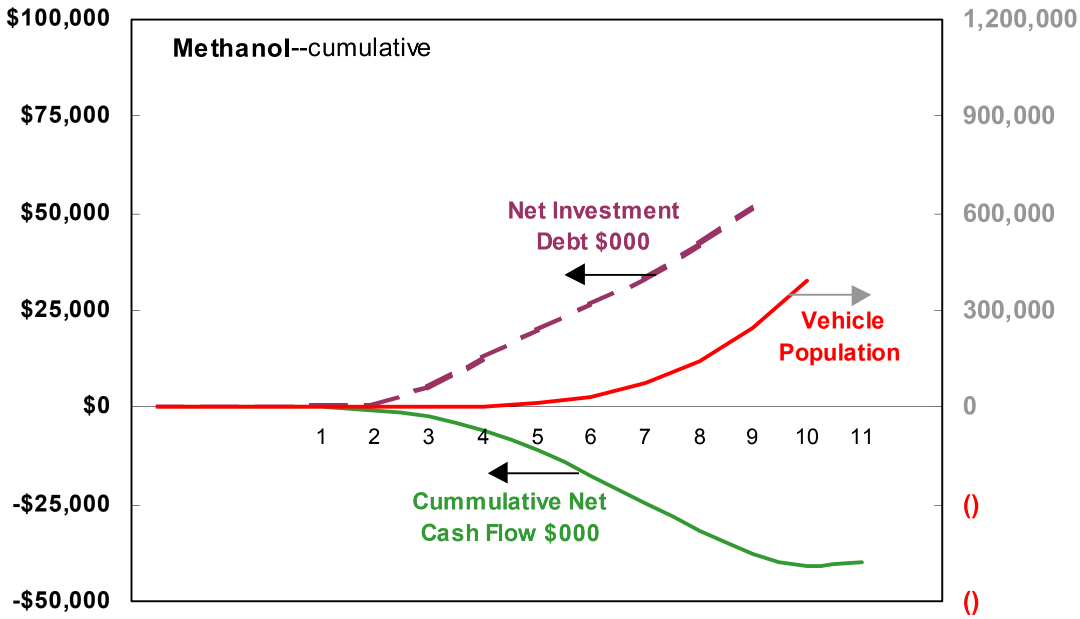


Exhibit 5-9: Illustrative Cumulative Cash Flows for Methanol



5.9.7. Methanol Infrastructure Financing Challenge

How can the required infrastructure investment be financed, both initially in California and later throughout the nation?

Refer to the more general discussion of this topic in Chapter 3 for background. For methanol, it is feasible but may be unnecessary to form investment consortia to share this financial investment risk and its potential returns.

The investment in <u>any</u> fuel's FCV infrastructure gains little if any economy of scale or experience from the California start, so essentially the infrastructure cost for the nation is roughly proportional to population or ten times greater than that for California…first to reach the 10% fueling station penetration level and then much higher to expand it gradually to more stations. This suggests a national net cash flow plus investment cost of some $1.2 billion for the first few years, based on California's estimated $58 million in total initial expenses net of revenue for 10% of *half* of the state's fueling stations plus an additional $1.8 billion over the following decade to expand the station network to at least 25% of all stations.

5.10. Methanol FCV User Costs and Financing

5.10.1. Retail Methanol Cost and Price

What will be the delivered cost of the fuel relative to the gasoline-equivalent retail price that the user can be expected to pay?

It is assumed here, as for all other FCV fuels, that methanol must from the outset be priced to be at least cost-competitive and preferably slightly superior to gasoline in comparable hybrid vehicles on a per-mile basis. The delivered price of fuel cell grade methanol must therefore be competitive with conventional gasoline per unit energy.

With production from remote natural gas and at estimated future CA methanol port prices (see Appendices E and I for details), the addition of all other cost components in the retail supply chain would produce a per-mile fuel cost of about 3.5 cents per mile**.** That is competitive with ICEVs although not with comparable hybrid vehicles. As discussed earlier, a wholesale methanol price of $0.65/gal combined with today's retail gasoline price of about $1.75/gal allows for a potentially viable long-term business for methanol.

A significant issue is the comparison of fuel costs if gasoline prices were to drop. Available studies and industry trends indicate that this can be possible without government assistance other than a degree of road tax relief in order to help cover station costs and encourage FCV adoption (Appendix I). Further government support should be explored as a prudent contingency to assure that the FCV user can rely on the competitiveness of the fuel price relative to gasoline.

5.10.2. Methanol Price Stability

As both gasoline and methanol wholesale prices fluctuate independently, how can methanol's retail price to FCV users be kept competitive?

The divergence of views on future methanol prices (as noted in section 5.8.1) suggests that the danger of pressure on future methanol prices and margins cannot be dismissed even if unlikely. Ideally, market mechanisms could be developed that would increase assurance of methanol price stability. One possible avenue of solution lies in innovations in price hedging strategies that secure long-term supplies of methanol for FCVs at competitive prices tied to the future price movements of gasoline. Through the commodities markets, buyers and sellers could in theory negotiate mutually satisfactory deals that peg methanol delivery prices to gasoline prices for extended terms with risks acceptable to each party.

As noted in Chapter 3's review of this issue for all fuels, this is not a standard use of such hedging mechanisms. It could require techniques such as quantity blocks with varying terms, take-or-pay penalties, and even government price supports for a limited term. A variety of intermediaries could participate in such transactions, including automakers and government authorities as well as fuel brokers and retailers. The point here is not that this is the only solution, but that price parity cannot be assumed. The use of future fuel market hedging is only one example of the kind of innovation that may be required if future FCV fuel price parity is deemed essential.

5.11. Methanol FCV User Support Services

Are there any special user support services required for methanol FCVs?

Support services for FCV users include insurance, maintenance and repair, emergency response, and resale/recycling, as discussed in Chapter 3. Methanol FCVs carry no special requirements in this area other than the focusing of emergency response training and capabilities to deal with methanol's particular vapor ignition characteristics, flame invisibility, and ingestion toxicity. Substantial experience in these aspects has been gained through decades of other methanol uses and regulation, and there should be no serious difficulties in the timely assurance of adequate emergency response.

Emergency response procedures are the principal area of need for planning and training. Because of its use in an earlier California alternative fuel vehicle introduction experiment, methanol emergency response procedures have evolved through training and field experience. Such procedures cover both vehicle and structure fires involving methanol, including those at stations. For example, use of water for methanol and methanol-blend fire suppression is avoided in favor of dry chemicals, CO_2, or alcohol-resistant foams, as cited by US DOE (1991). Such procedures should be documented, confirmed, and widely trained, along with ingestion responses such as the use of ethanol during the latent period and invisible-flame precautions such as straw broom probes.

5.12. Selected References for Methanol FCV Issues

American Methanol Institute, 2000. Looking Beyond the Internal Combustion Engine: The Promise of Methanol Fuel Cell Vehicles.

Energy Laboratory, Massachusetts Institute of Technology, October 2000. On the Road in 2020: A life-cycle analysis of new automobile technologies.

Hoekman, K. Chevron Research, Personal communication, March 2001.

Machiele, P., May 1990, Summary of the Fire Safety Impacts of Methanol as a Transportation Fuel. Society of Automotive Engineers, Technical Paper 901113.

Malcolm Pirnie, Inc., 1999. Evaluation of the Environmental Fate and Transport of Methanol in the Environment, for American Methanol Foundation.

EA Engineering, Science, and Technology, Inc., 1999. Methanol Refueling Station Costs, for the American Methanol Foundation.

$(S\&T)^2$ Consultants, Inc., 2000. Assessment of Emissions of Greenhouse Gases from Fuel Cell Vehicles, for Methanex Corporation.

Supp, E. How to Produce Methanol from Coal, Springer Verlag, 1984.

U.S. Department of Energy, October 1991. Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Technical Report Seven: Environmental, Health, and Safety Concerns.

U.S. Environmental Protection Agency, 1994. Methanol Fuels and Fire Safety, US EPA 400-F-92-010, Fact Sheet OMS-8, August 1994

6 Gasoline FCV Challenges and Solutions

6.1. Gasoline FCV Overview

A major potential advantage of gasoline FCVs is the prospect of a conventional fuel (e.g., future CARB Phase III gasoline, 20-ppm sulfur) that requires essentially no infrastructure changes or investment for FCV use. Sharing the use of a conventional gasoline among ICEVs, hybrids, and FCVs would be a great advantage for fuel suppliers. It would also eliminate the new health and safety concerns of other fuels, and would be most convenient and familiar for consumers considering early FCVs. Its only significant disadvantage, at least to some observers, is in its loss of the opportunity to diversify the transportation fuel source portfolio and to eliminate its environmental and energy security concerns—although the gasoline fuel cell vehicle's greater fuel economy still provides some advantages over ICEVs and hybrids in these respects.

Despite its infrastructure advantages, the gasoline FCV option presents major technical challenges in on-board reformer development—not only in producing a practical on-board petroleum fuel reformer but also in the ability of that reformer to process aromatics without coking and to tolerate gasoline's levels of sulfur and other potential catalyst contaminants. Industry opinion is strongly divided as to the likelihood of success in these efforts as well as their timing if they do succeed. However, successful development of a conventional-gasoline reformer is theoretically possible even if its timeline to market readiness is uncertain.

Recently some major fuel providers have suggested that they may choose to produce a new premium fuel even cleaner than the Phase III specification, with 20ppm or lower sulfur and therefore capable of use in either combustion engines or fuel cells (presumably with some additional on-board cleanup). This strategy requires the development of on-board fuel cleanup or a reformer and fuel cell system capable of processing the aromatics and residual sulfur of this "clean gasoline" fuel.

If the use of any conventional future gasoline proves impractical, an alternative path is to avoid the sulfur and aromatics issues by using a special fuel cell grade of gasoline or other petroleum refinery product such as naphtha, with negligible levels of sulfur (i.e., ~1 ppm) and other contaminants as well as a simpler structure without aromatics. This choice would require fueling infrastructure investments similar to those for other liquid fuels, and the development of a practical on-board reformer, though less difficult, would still be a significant challenge. This gasoline FCV assessment chapter analysis considers both options. Yet another possibility is that a non-petroleum pathway could be offered by Fischer Tropsch fuels such as synthesis naphtha.

Other concerns include petroleum-based fuel cell vehicle emissions and the economic production of such an alternative refinery product, both of which could limit the prospects for governmental regulatory and financial support for FCV commercialization.

6.2. Gasoline FCV Commercialization Strategies

6.2.1. Conventional Future Gasoline FCV

The choice between future conventional gasoline (including a special low-sulfur version) or a different fuel cell grade refinery product is fundamental. If a future conventional gasoline can be used in the on-board reformer, there are no major confirmed non-vehicular challenges to FCV commercial introduction—although the FCV with an on-board gasoline reformer will surely carry a substantial cost premium compared to a compressed-hydrogen FCV. The on-board gasoline reformer approach, if technically achievable, would allow the early FCV commercialization strategy to be much more flexible. However, sulfur contamination may yet prove to be a major problem for gasoline as well as other liquid fuels.

If the sulfur problem is solved and gasoline proves to have no other major fuel infrastructure concerns and costs, the focus of FCV commercialization could be wholly on reformer development and the more generic concerns outlined in Chapter 3 for all FCV fuel types. Even the pilot-phase emphasis on fleets could be relaxed somewhat because of the immediate widespread availability of the fuel. This would allow placing the pilot-phase vehicles with a broader range of initial FCV users, thereby increasing the range of uses involved, and possibly also permit an early public market introduction. Moreover, the elimination of fueling infrastructure construction and its time requirements could help make possible an easing of the FCV commercialization schedule by a year or more. This in turn would allow more time for reformer development, offset later by the possibility of a faster FCV sales ramp-up.

Due to the scarcity of gasoline-specific challenges to FCV commercialization, <u>this chapter will focus primarily on the requirements imposed if the alternative special-fuel path must be taken</u>. This is not an assumption that the simpler conventional-gasoline path cannot occur. The shift to the alternative special-fuel path has major impacts on the gasoline FCV's commercialization requirements.

6.2.2. Special-Gasoline FCV

A special fuel cell-grade refinery fuel could be less expensive to produce than gasoline, since there is no need to add process steps to maintain octane. The refinery can reduce sulfur content to less than 1 ppm using streams that require less processing: The main cost of sulfur removal for ICEVs is the need to add back octane enhancing ingredients. So a ~1 ppm sulfur fuel cell grade gasoline might be economical to produce for FCVs, but then it could not be used in ICEVs, so the fuel refiner and marketer would have added FCV-specific fueling investment or lost revenue at the retail level until FCV populations increased.

The reformer: With either type of refinery fuel, the successful commercialization of gasoline fuel cell vehicles will depend almost entirely on the development of a practical on-board gasoline reformer. Although beyond this study's prescribed scope, it should be acknowledged that this reformer's development to market readiness is particularly difficult and may occur later than that for other liquid fuels. Such a delay would necessitate the use of on-board compressed hydrogen or other fuel for at least the initial pilot phase vehicles, with a later transition to gasoline. Even so, it may be possible for this transition to be made with acceptable costs, particularly if governmental financial support or incentives were available for the pilot phase hydrogen vehicles and fueling.

Fuel characteristics: Since it is expected that the initial "gasoline" FCVs will require is a homogeneous, virtually sulfur-free mid-refinery product, the fuel's specifications and tolerances need to be identified immediately. Then existing refinery capabilities can be assessed to determine the needed modifications, if any, to plant and operations. This study's initial review of refinery processes leads to the conclusion that relatively minor changes will be needed and that these pose no challenge for the timely availability of the fuel as long as detailed refinery planning can begin at least 2-3 years before FCV introduction.

That sulfur-free fuel, such as the light straight-run (LSR) naphtha cut, may have a vapor pressure lower than that of conventional gasoline formulations. If this proves to be so, it will help to reduce evaporative emissions and may qualify the new fuel for a higher partial ZEV fuel cycle emission credit similar to that of the methanol FCV fuel option (0.6 for methanol vs. 0.2 for gasoline now). This regulatory issue should be considered and resolved as soon as the actual fuel can be identified, since it has major implications for government incentives and FCV industry go/no-go decisionmaking.

There are several other technical issues which this study predicts will be resolved routinely. The lower RVP would carry the possibility of creating a flammable vapor space within the fuel tank. This requires early study and resolution of associated safety concerns, but solutions already exist and no serious difficulties or delays are to be expected. This study assumes that the gasoline FCV will require an on-board trap capability for residual sulfur, e.g., zinc oxide. The trap system will require scheduled checking, renewal, and possibly alarms, but has no development obstacles that cannot be overcome routinely.

Fueling infrastructure: In an early pilot phase, the special FCV fuel can be provided through expansion of existing fleet refueling facilities plus modification of a few selected public gasoline filling stations. The required investment would be relatively small, but the very small quantities of fuel required would result in continuing deficits (as with all other fuels during this period). These may require public support; if so, efforts should begin as soon as possible to educate public policymakers and elected officials on the need and justification for such support. Adequate public policy support may be slow to develop, but must be in place two or more years in advance of commercialization.

The commercialization strategy for special-gasoline FCVs beyond the pilot phase includes a total reliance on existing gasoline filling stations. There are no technical or regulatory onsite fuel storage and dispensing challenges for a gasoline-like fuel. Tanks and pumps can be added; alternatively, as recommended for methanol or ethanol, mid-grade gasoline vending can be converted to on-demand blending from the other two grades and its existing tank converted to FCV fuel storage. The investment's payback is likely to be slow, due to the widespread infrastructure but relatively small amount of fuel needed during the first decade of FCV use. However, this situation can be managed through involvement of investment partners tolerant of long-term risks and payoffs, with limited incentives from government similar to those needed for other liquid fuels.

The following sections provide further details on the present situation, deficiencies, and recommended actions to provide the needed solutions, primarily for special-gasoline FCV commercialization. When the specific issue discussion applies also to conventional gasoline, it is so identified.

6.3. Gasoline and Naphtha FCV Challenges and Solutions

The following sections describe the key challenges for both gasoline and an alternative refinery product such as naphtha for FCV commercialization, this study team's expectations for the adequacy of current efforts, and recommendations for further solutions needed to assure success. As noted earlier, the major emphasis here is on naphtha due to the very few infrastructure issues faced by gasoline. These are organized by topic and challenge, as follows in Exhibit 6-1 on the following page.

Challenges considered in this study to be most critical are shown in bold type. Analyses and potential solutions for each challenge are presented in the corresponding sections of this chapter, in the order shown in the table.

Exhibit 6-1: Gasoline/Naphtha FCV Commercialization Topics and Challenges

Topic	*Potential Challenge*
Vehicle Technology Readiness	**Choice of petroleum-based fuel** **Reformer technology readiness** **On-board reformer cost**
Adequacy of Societal Benefits	Air pollutant emissions levels Greenhouse gas emissions effects Multimedia impacts Energy security and diversity
Public Health and Safety Concerns	Fuel ingestion hazards Fire hazards
Market Development Requirements	Consumer education Product packaging
Fuel Infrastructure Requirements	Fuel availability Refinery operations disruption **Fuel distribution difficulties** Fueling station modifications Infrastructure construction difficulties
Fueling Infrastructure Costs and Financing	Fueling station costs Fuel cost components Total infrastructure cost Infrastructure costs in context Stranded investment risks **Adequacy of business case** Infrastructure financing
User Costs and Financing Requirements	Fuel price acceptability
User Support Services Requirements	(none)

6.4. Vehicle Technology Readiness

6.4.1. Choice of Petroleum Fuel

What refinery product will be the "gasoline" fuel choice?

This study emphasizes the critical choice between two petroleum refinery products for fueling initial "gasoline" FCVs. These are

> (1, preferred) a premium future low-sulfur "clean gasoline" for use by both FCVs and conventional vehicles, as proposed by some major petroleum refiners within the CaFCP, and

(2) the best-available alternative refinery product for FCVs only, permitting less difficult on-board reforming in the event that the reformer for the preferred gasoline product cannot be successfully developed for commercial use.

Clean gasoline: There appear to be almost no infrastructure challenges or costs with gasoline, if the on-board reformer can be developed. One potential challenge has emerged in the form of reformer sulfur intolerance coupled with possible sulfur contamination risks in existing gasoline delivery. US DOE has recently reported experimental results to the study team indicating severe fuel cell performance degradation over time with sulfur levels as low as 200 ppb of H_2S, suggesting that even 1 ppm may be too high. This heightens concerns of contamination, particularly in sharing or conversion of pipelines and trucks from conventional gasoline to fuel cell grade products. This finding led to the suggestion that station-site gasoline cleanup may be required and that off-board reforming of hydrogen may prove to be a more practical gasoline pathway, as noted in Chapter 4. Note that the same contamination problem may apply to other liquid fuels.

If the sulfur contamination issue can be resolved, and the reformer can be developed successfully, gasoline faces virtually no other unique challenges to commercialization and is therefore not analyzed further in this chapter. The remainder of this chapter focuses on the broader challenges and solutions that may arise if the alternative refinery fuel must be used for FCVs.

Alternative refinery product: As discussed further in Appendix F, the study team has identified the LSR naphtha cut as the most promising non-gasoline refinery product for FCV use. This product is produced in California refineries for other purposes, and sufficient available capacity exists for the first decade of FCVs. The LSR naphtha cut exists in crude oil and is distilled out and desulfurized routinely. Its low octane requires further treatment for use in gasoline blending, but is an advantage for use in FCV reformers. This product can in fact be reformed to yield hydrogen with significantly less difficulty than gasoline, which permits a scenario in which the reformer cost can be lower and its development less complex.

Naphtha's delivered price is assumed to be below that of gasoline due to its ease of production and relatively low value as a blending stock. Production capability should be sufficient to begin FCV commercialization and growth for up to a decade or more, by which time possible future FCV fuel innovations could be phased in, e.g., either a conventional gasoline reformer or another FCV fuel option such as hydrogen. This reformer could also accept ethanol (see Chapter 7) alone or in naphtha cut blends, if national fuel security or environmental concerns dictate the greater use of domestic (and renewable) fuels.

6.4.2. Reformer Technology Readiness

Will the required on-board reformer be ready early enough to avoid causing a delay in FCV commercialization?

There appear to be no infrastructure technology challenges other than the on-board reformer. On-board gasoline (or naphtha) reformer technology must be proven by the time of the required automaker decision point for pilot phase commitment (or market entry phase decision point, if compressed hydrogen is used temporarily for the pilot phase) and quickly made economic in order to permit that phase to begin. That proof must be to the satisfaction of the automakers involved, and must also be demonstrated conclusively to prospective fuel providers in order to secure their commitment to invest in the needed infrastructure. This strategy may be necessary for at least some automakers. A detailed study of the specific reformer technology challenges is beyond this study's scope: However, timely reformer development success is widely acknowledged to be dependent on overcoming major technical challenges as soon as possible in order to avoid forcing a delay in FCV commercialization.

The reformer technology may be unable to deal with the level of sulfur in the then-available conventional gasoline, assumed here to be 20 ppm, or its aromatic content. If so, commercialization could still begin with vehicles using a much lower-sulfur naphtha fuel as noted earlier in this chapter. This would require substantial new fueling infrastructure investments that could be stranded by later success in improvements in the reformer, similar to other non-gasoline fuels, but such a strategy would permit the accelerated introduction of FCVs if considered necessary for environmental concerns or other reasons.

A situation could arise in which the reformer challenges would be largely overcome and remaining solutions are nearly complete but become the key delaying factor for the pilot phase, even with the naphtha fuel. In this situation a practical alternative may be for the pilot phase to begin with direct hydrogen FCVs. This approach would permit the pilot phase to begin earlier while allowing more time for the conventional-gasoline or naphtha cut reformer and the naphtha fueling infrastructure to be completed for market introduction.

6.4.3. On-Board Reformer Cost

What are the overall FCV cost implications of the gasoline or naphtha cut reformers?

As with the methanol reformer, both the gasoline/multifuel and the naphtha /multifuel reformer technologies that can be ready for either a pilot phase or market introduction may not be adequately cost-effective for mass market use. However, due to the relatively small volumes of vehicles to be built during these initial phases, the total cost premium may be low enough for either government support or manufacturer forward pricing.

For example, a $5000 interim gasoline reformer premium on the initial 3000 vehicles would result in a total premium of $15 million (alternatively, about $600 per year for the life of the vehicle or about $3.75 per conventional gasoline gallon-equivalent over an assumed 8-year vehicle life at 60 mpg-equivalent). However, if cost-competitive reformers were then to appear and the earlier excess cost amortized over the next 100,000 vehicles instead of only the initial 3000 involved, the cost premium per vehicle would be only $180 or less than $25 per year of vehicle life. Alternatively, if allocated to the fuel used by those 100,000 vehicles over an 8-year period, the premium would be about $0.11 per gallon-equivalent.

Note that this analysis assumes that the automaker is ultimately able to produce FCVs at acceptable market prices including the cost of the reformer. This will be a substantial challenge for all liquid fuel FCVs, and particularly for the relatively complex gasoline reformers. Judgment of this likelihood is beyond the scope of this infrastructure-oriented study.

6.5. Adequacy of Societal Benefits

Any FCV technology must demonstrate its contribution to a path toward improved societal benefits such as environmental quality in order to justify its costs to the society as well as to its developer, producers, and infrastructure providers. This section considers the available evidence of such potential benefits as a basis for public policymaking and investment decisionmaking.

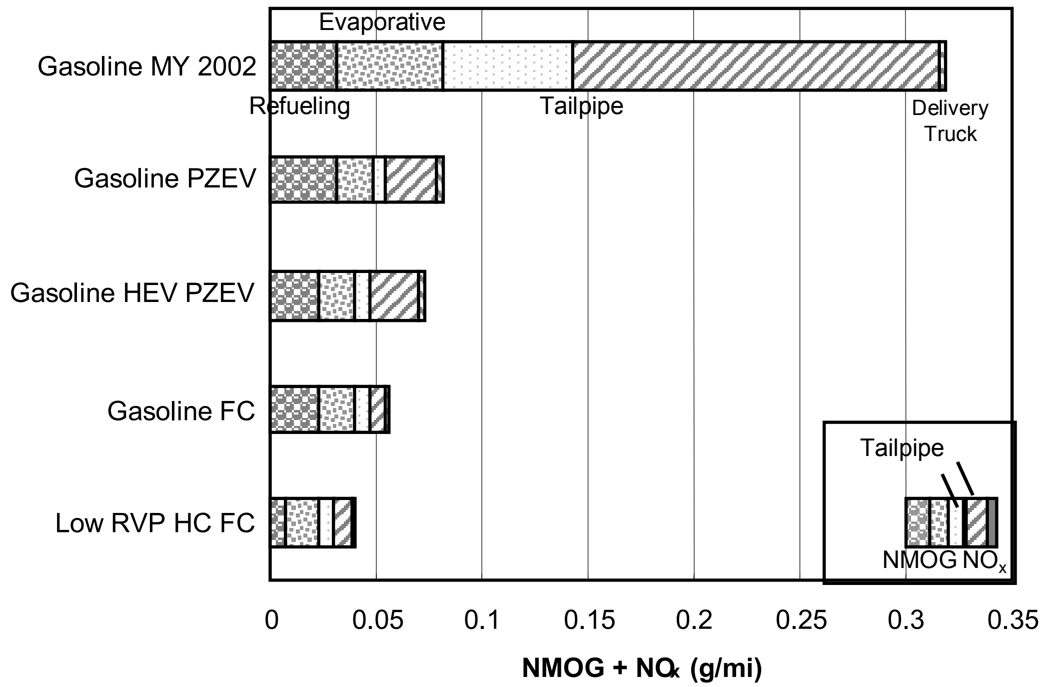
6.5.1. Air Pollutant Emissions Levels

What are the expected air pollutant emissions levels for GFCVs under the different fuel source and supply alternatives?

Exhibit 6-2 shows the local emissions related to gasoline vehicle operation. The figure compares conventional gasoline vehicles that would be built late in this decade with PZEV certified gasoline vehicles, HEVs, and fuel cell vehicle options. PZEV certification results in lower exhaust and evaporative emissions. While a PZEV certified vehicle is required to have a "zero evaporative" fueling system, inventory assessments include some evaporative losses. These are largely due to certification allowances and have been adjusted downward for these comparisons. While exhaust and evaporative emissions are reduced with PZEV certified vehicles, these vehicles provide no reductions in refueling emissions. These emissions are largely proportional to fuel economy and therefore are reduced with hybrid and fuel cell vehicle operation as these vehicles would have improved fuel economy compared to conventional vehicles. Similarly, NO_X emissions associated with fuel delivery trucks are also reduced as vehicle fuel economy improves.

Emissions for a low vapor pressure hydrocarbon such as naphtha were also estimated. A low vapor pressure fuel would eliminate much of the emissions from vapor losses. However, emissions from vehicle fueling spillage would still occur. Fuel cell vehicle operation was also assumed to reduce NO_X emissions lower than PZEV levels. This assumption is based on limited data from vehicles and stationary hydrogen generation systems that might have NO_X emission characteristics similar to vehicles equipped with on-board reformers. From this examination it may be concluded that gasoline FCVs using either standard pump grade gasoline or a low-sulfur/ low-RVP refinery product will have local air pollutant emissions significantly lower than those of a gasoline/battery hybrid.

Exhibit 6-2: Smog Precursors from Gasoline Vehicle Operation



6.5.2. Greenhouse Gas Emissions Effects

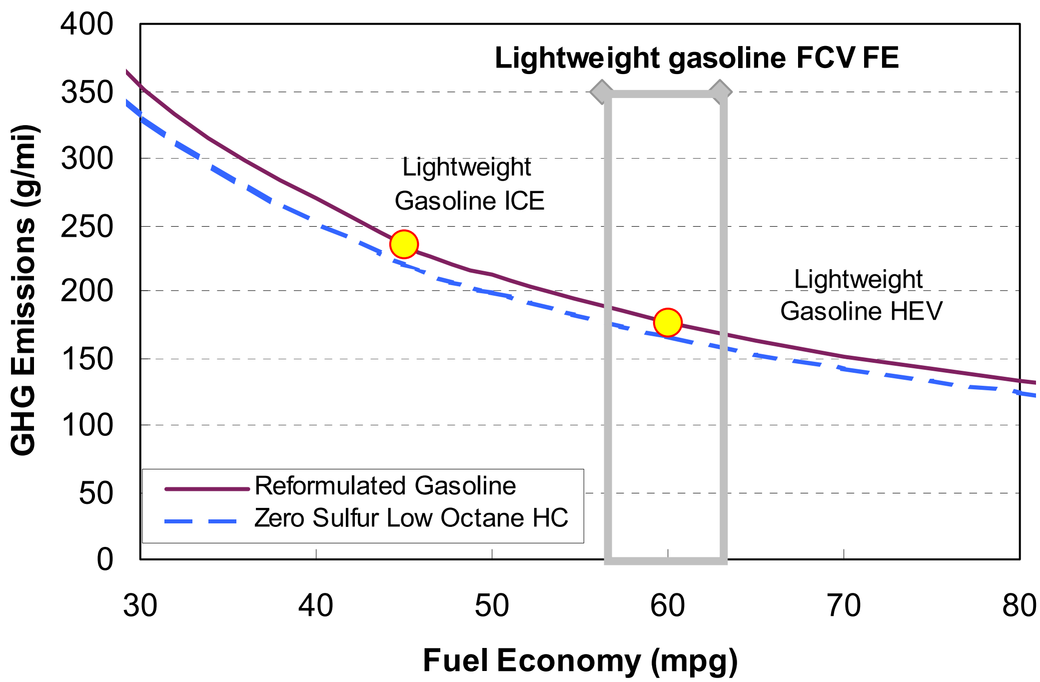
What are the greenhouse gas emissions effects of GFCVs under the gasoline and naphtha fuel supply options?

Based on best-available evidence in study team experience and literature, Exhibit 6-3 presents the study's derivations of the GHG emissions for several varieties of conventional gasoline vehicles plus FCVs using two different gasoline fuels: a future premium low-sulfur fuel otherwise similar in emissions characteristics to California RFG/2007, and a zero-sulfur/low-RVP petroleum refinery product that may be an alternative early "gasoline" FCV fuel.

This study's results indicate that the conventional gasoline FCV has greenhouse gas emissions slightly higher than those for a practical gasoline/battery parallel hybrid vehicle. The alternative refinery fuel with zero sulfur performs slightly better, reducing gasoline FCV emissions of GHGs to a level just below those of the hybrid although still within the range of uncertainty. This indicates that although gasoline FCVs essentially offer no GHG emission advantages, they are on a par with hybrids, well within the European standard, and far superior to conventional ICEVs.

Although not shown in Exhibit 6-3, a renewable component could be added to the gasoline scenario by blending with ethanol. The effects of such an approach are assessed in Chapter 7's ethanol scenario.

Exhibit 6-3: GHGs for Gasoline FCV vs. Hybrids and FCV Alternatives



6.5.3. Multimedia Impacts

Will naphtha or gasoline have "multimedia" (soil and water) advantages or impacts requiring further effort in understanding, regulation, and/or mitigation?

As with other FCV types, the gasoline FCVs provides a power plant that does not use lubricants in the same manner as an internal combustion engine. Lubricating oil changes and associated spill contamination of groundwater can therefore be reduced compared with ICE operation. To the extent that fuel economy is improved with FCVs, there will be a reduction in gasoline demand and associated fuel-spill impacts associated with expansion of refinery capacity, fuel transport, and use. The fuel consumption of gasoline FCVs will be similar to or slightly less than that of comparable HEVs, so impacts related to fuel production will be modest. However, although diminished by this reduced fuel usage, the current soil and groundwater contamination effects arising from gasoline fuel spills and tank leakage will continue.

6.5.4. Energy Security and Diversity

Would gasoline or naphtha-fueled FCVs contribute significantly to national energy security or diversity?

Gasoline and naphtha-fueled FCVs are assumed in this study's analyses to use petroleum feedstocks. At the margin, these feedstocks are imported from foreign sources around the globe. This FCV fuel therefore provides no improvement in national energy security or diversity. However, it is also possible to use Fischer Tropsch synthesis naphtha. If economically feasible, this would shift the sources to remote natural gas fields similar to the methanol feedstock sources, yielding a measure of fuel diversity if not obvious security improvements.

The gasoline/naphtha FCV is also projected in this study to offer a small improvement in fuel economy relative to that of a comparable hybrid battery/ICEV as well as a substantial improvement relative to future pure ICEVs. This fuel economy improvement, assuming no CAFE-driven automaker fleet offsets, would constitute a small but real improvement in energy security.

6.6. Public Health and Safety Concerns

Gasoline safety regulations are well developed and understood after decades of experience. However, a naphtha-like gasoline alternative has significantly different characteristics and will require some new review and possible experimental verification once the precise composition is selected. In this study only two potential concerns were identified: the fuel's possible acute toxicity and the creation of a flammable vapor space. Depending on the fuel formulation, these may or may not require remediation. Further review is needed by the appropriate industry standards committee, yielding new standards if needed for incorporation into local building codes and inspection practices.

6.6.1. Fuel Ingestion Hazards

Are further measures needed for protection against gasoline or naphtha-like fuel ingestion?

This issue is of potential concern only because of the historical evidence of many cases of gasoline poisoning--reportedly some 30,000 cases of emergency treatment annually in the US. These are apparently due mostly to attempts to siphon fuel from tanks. However, the principal effect is gastric upset and vomiting, and deaths are rare. In addition, this hazard already exists and will not be increased by FCV use if the alternative gasoline fuel introduces no new acute toxicity effects beyond those of gasoline. This study suggests that no significant toxicity problem will be found for naphtha that requires action beyond safeguards already in place for standard gasoline, although for any such specialty fuel a formal study of its health effects should be undertaken to assure safety prior to vehicle development.

6.6.2. Fire Hazards

Will a naphtha-like fuel's low RVP result in a need for special measures to protect against fire or explosion arising from a flammable vapor space in fuel storage on-board the vehicle and throughout the supply chain?

Flammable vapor space creation, with its potential dangers of ignition in storage tanks throughout the fuel supply chain including on-board the vehicle, is not a problem with standard gasoline due to its high RVP. The flammable vapor space possibility has been raised for non-gasoline refinery products such as naphtha, due to the low RVP of such fuels compared to that of conventional gasoline. This issue is well studied for alcohols with similar low RVPs. Standard mitigations already practiced with methanol and ethanol fuel (e.g., spark arrestors, foam tank fillers, etc.) should suffice.

Other potential fire hazards of gasoline are well documented and will continue with gasoline FCVs. A variety of gasoline characteristics combine to create significant fire risks, along with injuries, deaths and property damage, generally due to fuel tank ruptures or leaks. Despite these risks, gasoline FCVs will reduce these present fire dangers somewhat because of reduced fuel use.

The only further effort recommended from this study, as for methanol and ethanol's similar low-RVP characteristic, is the formation of an industry committee to address the need and opportunities for effective mitigation measures and requirements for such a non-standard fuel.

6.7. Gasoline FCV Market Development

6.7.1. Consumer Education Effort

Are there significant consumer education efforts unique to gasoline or naphtha-like FCVs?

Consumer education efforts unique to petroleum-based FCV fuels have to do with its environmental implications, specifically to promote public understanding and acceptance of its long-term transitional role. As a market-development tool, education efforts should focus on the continuation of petroleum-based fuels as "the path to the future" (i.e., a transition to on-board hydrogen storage in later decades). The current conveniences and long-term environmental benefits of the "gasoline pathway" for FCVs should be stressed through a cooperative media program. This program could be jointly supported by government and industry. A crucial step in this approach will be to gain the early support of the environmental community.

This educational program should begin a year or more before the pilot phase and would focus first on fleets in preparation for the pilot test phase. Due to inevitable national media attention on FCVs by that time, a broader public-targeted campaign will also be needed nearly as early. That campaign will continue at least a year after FCV market introduction, alternating with periodic panel-type market research to gauge the development of public attitudes toward petroleum-fueled FCVs.

6.7.2. Product Packaging

What gasoline-specific FCV product packaging components might be needed?

Chapter 3 included a detailed discussion of the need for a comprehensive "product package" to provide maximum competitive value for all FCVs. There appear to be no additional product packaging aspects of GFCVs other than education on the long-term rationale for continuing to use gasoline (as discussed earlier in this chapter) despite current long-term supply and environmental concerns. If use of a naphtha-like substitute proves necessary, the relative environmental advantages of that fuel and (as for the other non-gasoline fuels) assurances of its future price competitiveness should be stressed.

6.8. Fuel Infrastructure Requirements

6.8.1. Fuel Availability

Will sufficient gasoline FCV fuel feedstocks and fuel product be available as needed?

Fuel feedstock sources and processing capability for petroleum-derived FCV fuels appear to be ample. No new feedstock sources would be needed: Oil would be used that would otherwise be produced and refined for ICEV use. The improved fuel economy of FCVs should be a benefit in this regard, resulting in a net reduction in petroleum required for transportation.

However, the projected rapidly increasing global demand for petroleum-based fuels may push prices up, both due to increased market competition and the increasing costs of oil exploration and recovery as known resources are depleted. This can lead not only to increased direct costs but also major indirect governmental costs for maintaining order in the oil markets and delivery channels (International Center for Technology Assessment, 1998).

6.8.2. Refinery Operations Disruption

Will the use of a naphtha-like alternative fuel for GFCVs cause significant changes in refinery configuration and multi-product optimization?

Fuel refining for a new homogeneous petroleum-based fuel, according to this study team's refinery experts, can be incorporated readily into existing refineries. Refinery inputs and outputs are optimized based on all cost elements vs. multi-product market conditions. However, the naphtha fuel identified here as a gasoline alternative for FCVs has substantial production capacity and flexibility in California refineries, and no significant modification is anticipated either to refinery operations or capabilities for at least the first decade of FCVs.

For this study, the total annual FCV fuel quantity requirement during the initial commercialization period ranges from 100,000 gallons in the pilot phase to approximately 10 million gallons by the time the 40,000 vehicle/year milestone is reached several years later. Compared to the 14 billion gallons per year now produced for the California gasoline market, these early-market FCV fuel estimates constitute between 0.07% and 0.17% of total production. At such small incremental volumes, very small adjustments in refinery operations will suffice without significant new investment in refinery facilities. Such investments will not be needed for some years after the 40,000 vehicle milestone, so long as an existing product such as naphtha is found to be suitable for FCVs. This study's review suggests that this will be the case. For a more detailed discussion of this topic see Appendix F.

Naphtha is considered a low-value blending stock. In the long term, this study's current best estimate is that for naphtha its relative simplicity and capacity of production will more than offset any investments in refinery facilities plus the costs of special handling and delivery for FCVs. This suggests that such fuels for FCVs can be produced and delivered at a price below or equal to that of gasoline. During the first several years of FCV introduction, the refiner's cost may be somewhat higher due to the low fuel volume required and its disproportionate "nuisance" costs, but this assessment concludes that the price can still be immediately competitive with gasoline.

6.8.3. Fuel Distribution Difficulties

Will gasoline FCV fuel distribution from refinery to stations pose major new costs or other concerns?

Fuel transport and delivery for petroleum-based fuels involve pipeline and truck shipment for which conventional technology is satisfactory and capacity available. This is similar to the conventional means of gasoline fuel transport, and has been generally assumed to use many of the same facilities and procedures although some segregation of product tankage and trucking might be required. Transfer via existing shared-product pipelines and trucks for very low-sulfur fuel, if required, may pose potentially serious fuel contamination challenges due to sulfur in tails from other fuels shipped.[12]

This problem has also been shown to occur in trucks in past methanol and ethanol introductions: A careful implementation of procedural safeguards is required, and contamination risks may only be avoided with dedicated trucks. If a naphtha-like alternative fuel is used, conventional gasoline safety procedures may suffice although a transport safety review should be conducted and standards established.

---

[12] A recent article in *New Fuels & Vehicles Report* (June 21, 2001) reported on a similar issue facing the pipeline transfer of the ultra-low sulfur diesel fuel under the US EPA specification for 2006. Because of the possibility of contamination due to the carbon steel pipe's absorption of sulfur from other products and possible transfer into the low-sulfur diesel, the Association of Oil Pipelines is reported to believe that refiners will have to produce diesel fuel with a sulfur content below 10 ppm in order to ensure that the finished product confirms to the 15 ppm requirement.

This problem also applies to other liquid fuels, including any low-sulfur pump grade gasoline. Early resolution is required so that technology requirements and cost effects can be properly assessed.

6.8.4. Fueling Station Modifications

What physical changes to fueling stations will be needed to accommodate gasoline FCV fuels?

If conventional gasoline is used for FCVs, obviously no station modifications will be needed. If, instead, a special fuel such as naphtha is needed, fueling facilities can be provided by modification of existing gasoline stations. Typically the addition of this special fuel's storage and vending capability will involve the addition of pumps and either a new underground tank or the conversion of an existing tank from gasoline to the naphtha-like fuel. This study found no significant tank conversion costs for this fuel, although this conclusion must be tested against the actual fuel formulation chosen. However, if gasoline revenue is not to be lost, the conversion of an existing tank at most stations would require either the elimination of the mid-grade gasoline option or its onsite blending from the premium and standard grades using new piping, pumping, and metering equipment. In addition, to guard against misfueling, the new fuel would require new dispensing equipment incompatible with conventional ICEV fuel tanks.

6.8.5. Infrastructure Construction Challenges

Can enough stations be modified for naphtha-like fuel quickly enough to avoid delaying commercialization?

The analysis of Chapter 3 applies fully to this fuel alternative. Modification of 500 existing stations in 4 years would need to occur at a constant rate in order to provide minimally acceptable access to fuel for the early public-market FCV users. Front-loading of the station population is unnecessary, since marketing selectivity can be used to control both where the initial vehicles are sold and the needs of their earlier adopters. This study concludes that approximately 100-125 stations per year, or about 8-10 per month, is a substantial but not overwhelming construction task, particularly if several major fuel providers are involved. This rate of tank replacement and station upgrading is similar to or less than that observed during the recent years of required underground tank upgrading for thousands of stations throughout the state. In addition, the construction efforts, special materials, and skilled labor required are not materially different from those same factors as applied in the earlier gasoline tank upgrading.

6.9. Fueling Infrastructure Costs & Financing

As with other FCV fuels, a complete infrastructure financial analysis must include the fueling station operating costs attributable to the GFCVs. The combination of capital and operating costs over time can then be compared with the revenue stream to assess factors such as cost recovery and return on overall investment. Conventional gasoline use requires no additional operating costs, since current equipment and fueling procedures would be used. The separate facilities needed for a naphtha-like fuel, however, will carry some additional operating costs. Assumed station operating cost components for a naphtha-like fuel are as follows**.**

6.9.1. Fueling Station Costs

What is the estimated cost of typical naphtha fueling station retrofits?

This study's estimates of conversion requirements, including maintenance of the mid-grade gasoline fuel capability through blending, indicates the average investment cost for modifying a typical mid-size station for this new fuel to be the same as for the other liquid fuel alternatives. This cost is in the range of $70,000, based on a mix of different costs for stations requiring new tanks, tank retrofits, or simple cleaning and reuse (see Section 5.9.1 for details). This includes applicable overhead costs and contingencies. Risks of major unanticipated additional costs are low due to the well-understood tank replacement process involved.

6.9.2. Naphtha Fuel Cost Components

What is the assumed production cost basis for naphtha FCV fuel during the market introductory period?

This study's analysis of naphtha fuel cost and pricing was built on estimates of key cost components. A wholesale cost of $1.07 was assumed, based on current gasoline pricing; no cost savings was assumed for naphtha's lower production cost, although such savings may be possible. Standard estimates of storage and transport costs, various taxes, terminal costs, and truck transport are added. The amount available for coverage of the capital infrastructure costs is then derived by deducting those cost components from the "target" fuel unit price, which is the naphtha equivalent of the per-gallon gasoline price for a comparable ICEV. This results in retail fuel price parity with gasoline.

The study's illustrative estimates of fuel-equivalence assumptions and naphtha cost components are shown in Exhibit 6-4.

Exhibit 6-4: Fuel Cell Naphtha Fuel Cost Components

Parameter	*Value*	*Unit*
Gasoline subcompact fuel efficiency (FE)	45	mpg
Benchmark competition (Hybrid EV)	56.2	mpg
Benchmark HEV energy efficiency ratio	1.25	Btu/Btu
FCV EER, estimated	1.39	Btu/Btu
FCV FE result (mpg naphtha)	62.6	mpg
Retail gasoline price	1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Retail Naphtha Price Target, w/tax (ICEV-equivalent, based on relative fuel economy)	**1.89/gal**	
Wholesale Naphtha	1.07	$
Storage	0.02	$
Truck transport	0.05	$
Federal tax	0.184	$
CA excise tax	0.18	$
CA Sales Tax	0.12	$
Derived residual to cover capital costs & return	**0.25**	**$**

6.9.3. Total Estimated Initial Infrastructure Cost

What is the total capital outlay for the initial California commercialization period?

For the minimum of 500 stations estimated to be required for market introduction in California (see Chapter 3 for further details on the derivation of this quantity), the total station investment is approximately 500 x $70,000 average or $35 million over an assumed 4-year period. This number of stations would continue to rise after this point to an ultimate population that will be determined through user response--but expected by CaFCP fuel marketers to require at least 15-20% of the state's existing ~9500 stations.

The infrastructure financial analysis includes both the fueling station net cash flow elements in addition to the capital investment attributable to the FCVs. The cash flow includes interest and capital recovery payments, a share of the station's total fixed costs, plus variable costs attributable to FCVs such as fuel purchases, equipment maintenance, repairs, and additional electricity requirements, all net of fuel revenue. The study's cash flow and investment model results for both cumulative current-year costs and NPV are shown in Exhibit 6-5. Further details are in Appendix E.

Exhibit 6-5: Naphtha Transitional Fueling Infrastructure Investment Results

Through year 7	*$(000)*	
Total capital-only investment in 500 stations	$35,000	
Net negative cash flow plus capital investment	$57,212	(40,000 v/yr)
Net Present Value	$36,532	

6.9.4. Infrastructure Cost in Context

What are the costs of the naphtha FCV fueling infrastructure relative to the fuel costs of the FCV user and the conventional ICEV owner?

For the naphtha refueling station infrastructure, Exhibit 6-5's estimated early $57 million in capital investment and net operational cash flow losses through the 40,000 vehicles/year milestone can be viewed in a variety of ways, including the perspectives of FCV users and all California drivers. This is of interest because of the widespread societal benefits that may result from FCV use.

If the first decade of FCV owners (i.e., up to when the original infrastructure might begin to need renewal, estimated at approximately 1 million FCVs) had to pay for all of it, the cost would be about $60 each, or around $0.04 per gallon throughout that initial decade…a significant price premium. However, from the perspective of current California gasoline use, now some 14 billion gallons per year, the cost of the initial GFCV infrastructure amounts to less than half a cent per gallon for one year…or about two dollars per car as a one-time payment.

6.9.5. Stranded Investment Risk

What is the risk of stranded early investment in a naphtha-fueling infrastructure?

The naphtha FCV station retrofit investment during the pre-40,000 vehicle per year introductory period in California, including operating costs net of revenues, is estimated in this study at some $57 million, as shown above in Exhibit 6-5. The risk of stranding of this early investment is low, since most of the new station infrastructure could be converted later if a different liquid fuel proved superior either for FCVs or alternative-fuel ICEVs. As with all FCV fuels, this stranded investment risk increases rapidly beyond the introductory period and the California locale, but is limited by the infrastructure re-use potential.

6.9.6. Adequacy of Business Case

What is the business case for investment in this early infrastructure?

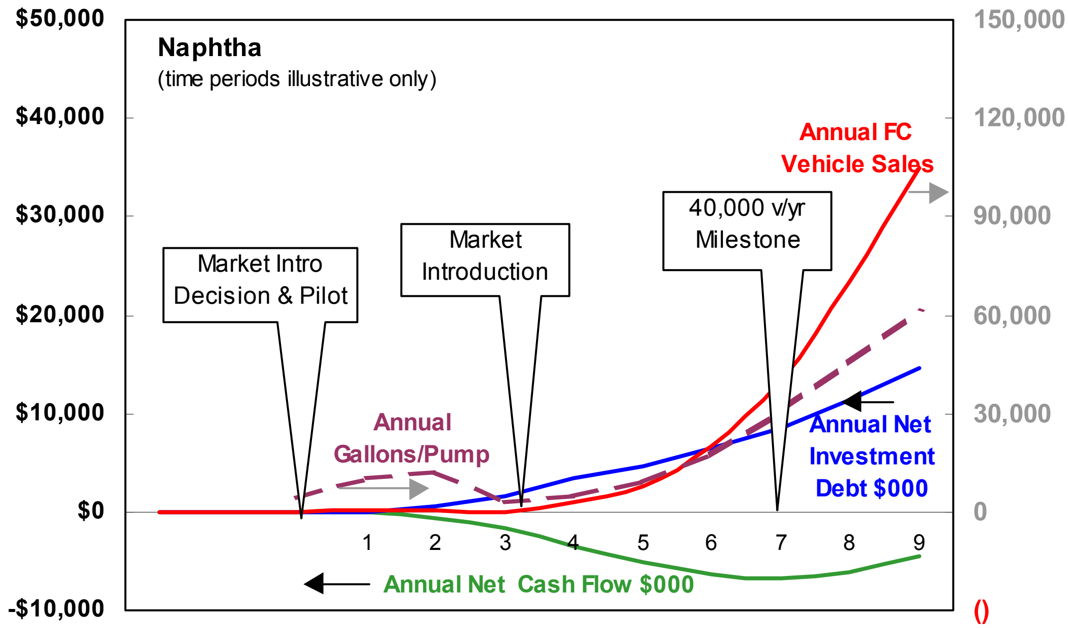
Clearly the business case for a conventional gasoline is satisfactory, since no new investment is required. The only negative factor for fuel retailers is that the total quantity of fuel sold will be reduced due to FCV fuel economy gains, and in this study's analysis of the introductory period even this is projected to be very small.

As with all FCV fuels, the naphtha infrastructure business case is made difficult by the fact that these new FCV fueling facilities will dispense very little fuel for the first several years, since so few FCVs will be in use during this period. By the time either the 40,000 or 100,000 vehicles/year milestone is reached, FCVs in use will total less than one percent of the statewide vehicle population despite having fueling facilities in at least 5% of the state's conventional filling station locations. The new FCV fueling equipment will thus produce far less revenue to cover its investment and operations costs until well beyond the interim 40,000 vehicles/year milestone.

In this study the financial implications of the required investment amounts and timing were modeled, continuing beyond the 40,000 vehicle milestone, versus the rates and timing of the revenue and cash flow cost streams anticipated for the market development scenarios of this study. As with the other fuels in this study, input variable values used in this cost modeling were the most conservative possible while yielding an approximately similar annual positive cash flow crossover—approximately ten years after market introduction and 4-5 years after reaching the 40,000 v/yr interim milestone. As Exhibit 6-6 shows, further investments and cash flow losses will still be required beyond that point.

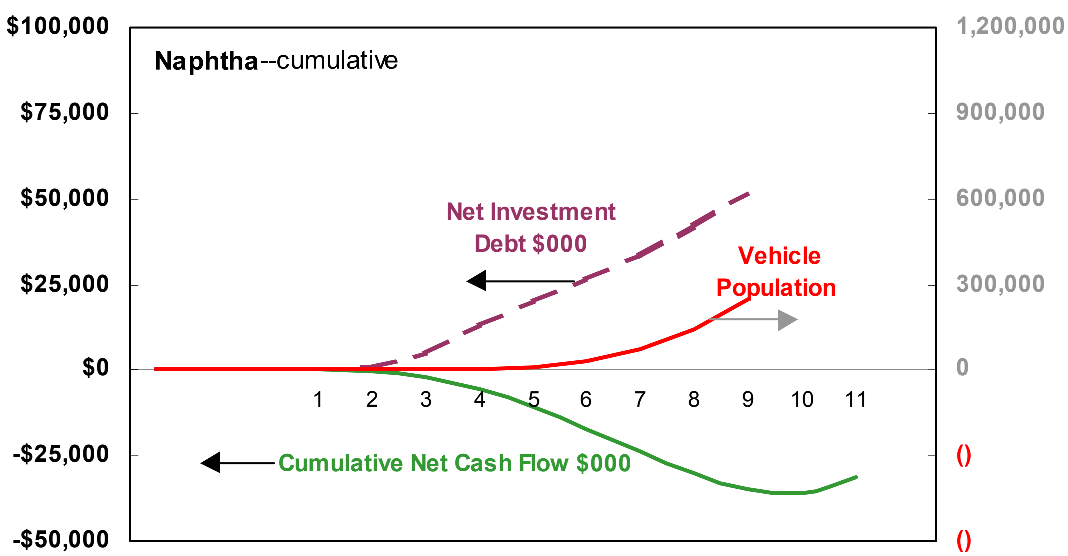
Exhibit 6-7 extends this analysis by showing the same variables on a cumulative basis, demonstrating the longer time required to recover the early investments and reach a net positive cash flow position.

Exhibit 6-6: Naphtha Fueling Infrastructure Cost and Revenue Projections



Note: Ultra low sulfur gasoline is also considered in this study. Available information indicates that its infrastructure costs for fueling stations are likely to be insignificant; see text.

Figure 6-7: Cumulative Cash Flow for Naphtha



6.9.7. Infrastructure Financing Difficulties

How can this level of fueling infrastructure investment be financed?

Refer to the more general discussion of this topic in Chapter 3 for background. For conventional future gasoline, no new infrastructure cost and no financing needs have been identified. For LSR naphtha, as with the other liquid fuels, it is feasible but may be unnecessary to form investment consortia to share this financial investment risk and its potential returns.

The investment in <u>any</u> fuel's FCV infrastructure gains little if any economy of scale or experience from the California start, so essentially the infrastructure cost for the nation is roughly proportional to population or ten times greater than that for California…first to reach the 10% fueling station penetration level and then much higher to expand it gradually to more stations. See Chapter 5 for a perspective on these infrastructure costs.

6.10. User Costs and Financing

6.10.1. Fuel Price Premiums

What will be the delivered cost of the fuel relative to the gasoline-equivalent retail price that the user can be expected to pay?

The true all-vehicles gasoline option would sell at a standard gasoline price unless it is a new super- premium grade that might not be used by many ICEVs. Even with such a premium price, if small, the FCV user may be at an advantage due to the FCV's higher effective fuel economy as projected in this study.

This study's refinery analysis indicates that a naphtha-type fuel in the quantities required in California through at least the 40,000 v/yr milestone can be produced at lower cost than gasoline (Appendix G). The primary cost uncertainty in the early years is the refinery operator's price for the "nuisance factor" associated with vending such a small quantity, adjusting other operations to make up for its loss to other processes, and handling the overhead costs such as scheduling and billing. Because of its relatively low production cost, the delivered price of a fuel cell grade naphtha-like FCV fuel can be competitive with conventional gasoline per unit energy in the long term, when the FCV population reaches a significant level--well after the 40,000 v/yr level. However, initial pricing support will be needed until vehicle and fuel volumes reach adequately cost-efficient levels.

A basic assumption here, as for all other FCV fuels, is that a naphtha-like FCV fuel must from the outset be priced to be at least cost-competitive and preferably slightly less expensive than conventional gasoline in ICEVs and hybrids on a per-mile basis. This study's assumed standard is $1.89 per gallon including all taxes, or approximately 3.1 cents per mile at an assumed 62.6 mpg (per Exhibit 6-4).

6.11. Gasoline FCV User Support Services

Does the gasoline or naphtha FCV present any unique user support challenges or opportunities?

As described generically in Chapter 3, support services for FCV users include insurance, maintenance and repair, emergency response, and resale/recycling. Neither gasoline nor naphtha-fueled FCVs carry any special requirements in this area, due to many years of experience and regulation of vehicular gasoline use. Assuming that the generic needs are met as outlined in Chapter 3, there should be no difficulties in the timely assurance of adequate user support services for gasoline FCVs.

6.12. Selected References for Gasoline FCV Issues

International Center for Technology Assessment, 1998. *The Real Price of Gas*

National Petroleum Council, 2000. *U.S. Petroleum Refining—Assuring the Adequacy and Affordability of Clean Fuels.*

Energy Laboratory, Massachusetts Institute of Technology, October 2000. *On the Road in 2020: A life-cycle analysis of new automobile technologies.*

7 Ethanol FCV Challenges and Solutions

7.1. Ethanol FCV Overview

This section presents the major unique aspects of ethanol fuel cell vehicle commercialization. Even with other ethanol uses considered, including MTBE replacement in California as well as many other parts of the nation, the required ethanol for FCVs could be supplied by existing sources outside California. However, there may be value in developing an ethanol industry within the state due to the added employment and income, possible forest fire reductions, elimination of harmful agricultural waste disposal practices, and greenhouse gas benefits. The possible use of California agricultural, forest, and urban wastes as renewable feedstocks is a major possible environmental benefit of ethanol, resulting in net GHG emissions far lower than any other FCV fuel options (except methanol or hydrogen from the same feedstocks, which would have similar GHG performance).

The greatest benefits from ethanol would be captured by using US-produced ethanol, thereby reducing crude/finished petroleum product imports. However, other sources are available. The worldwide ethanol production industry is very large, and huge quantities are produced and used as fuel, particularly in Brazil. Smaller but substantial volumes are produced in Canada. Collectively, annual world ethanol production from fermentation approaches 5 billion gallons.

Because of its compatibility with gasoline reformer technology, ethanol presents more than one FCV fuel option. Alone, it could be used with only a denaturant added (per federal requirements) for ingestion and fire safety. Alternatively, depending on limitations on economic production capacity, it could be used as a blending component with gasoline (or naphtha) preferably at levels above 40% ethanol to mitigate any effects on RVP. In either option, it could also be used on a region-specific or even location-specific basis in parallel with gasoline. A major advantage of this flexibility is that these alternatives could be changed over time as the numbers of FCVs grow and relative fuel prices vary.

With any fuel formulation, a major obstacle to ethanol FCVs is the development of a cost-effective on-board ethanol-capable reformer, which is similar in technology and difficulty to gasoline reformers and much more challenging than methanol reformers. Other issues include fuel ingestion concerns, flame invisibility, low RVP-related dangers, the cost and investment risk of building a complete California ethanol infrastructure from production through delivery, and the long-term adequacy of ethanol supply and economics. Ethanol's relatively high cost compared to gasoline, in particular, is likely to make it viable only as part of a flexible dual-fuel strategy in anticipation of a rising trend in gasoline prices.

7.2. The Ethanol FCV Commercialization Strategy

Ethanol strategy options include all-ethanol, blending, and flexible parallel fueling of ethanol and gasoline. A long-term all-ethanol FCV fuel approach appears infeasible due to clear supply constraints even with use of all realistic feedstock options. A blending strategy would also eventually result in ethanol supply and cost difficulties due to the >40% ethanol constraint. Instead, this study's proposed strategy for ethanol FCVs is to use ethanol and gasoline/naphtha in a parallel approach, with ethanol and gasoline used separately as complementary fuels sold in different areas or stations. Essentially the same multi-fuel high-temperature on-board reformer technology is required for both, with appropriate joint optimization via fuel sensors and feed-rate controls.

Each fuel could be supplied and used in the same FCVs at different times and places to optimize the economics of ethanol production and use for three refinery markets: FCV fuel supply, conventional gasoline oxygenation, and octane enhancement. For example, the natural seasonal variations in biomass feedstock supply could be taken into account, as well as the costs of alternative supply sources and demand-leveling seasonal ethanol storage. In general, ethanol would not be used in FCVs until its wholesale price premium relative to gasoline disappeared due to a variety of market forces—but the vehicle reformer technology and fueling infrastructure would then already be in place to permit this shift whenever needed, thereby providing an important degree of fuel flexibility.

This dual-fuel strategy may also respond well to a variety of environmental needs at once, with costs justified by the uniquely combined societal benefits:

- providing FCVs with a fuel option that is low in smog precursors as well as extremely low in net new greenhouse gas emissions,
- thinning forests of fire-prone undergrowth and timber slash,
- relieving farmers of the problem of crop wastes such as rice straw and reducing urban landfill requirements,
- oxygenating ICEV gasoline as needed,
- encouraging a California biomass-based ethanol industry in the near term and major growth in the national ethanol industry in the longer term, and
- creating a ready all-domestic and renewable alternative to gasoline (at least for FCVs) in the event of future petroleum price or supply disruptions.

Gasoline oxygenation needs could easily make use of all the California ethanol production capacity that could be developed within the coming decade (CEC, 2001). The additional ethanol needed for FCVs could be shipped from Midwest producers, who can expand production substantially as needed.

The full economic and environmental implications of this complex multipurpose strategy will require more detailed analysis than possible in this initial study effort. If the ethanol option is to be pursued, further study should focus on optimizing the scale and timing of the various ethanol sources that could be used, ranging from existing out-of-state corn-based production at the outset to later use of local forest and agricultural wastes and eventually to energy crops grown locally to provide transportation ethanol. This analysis would also incorporate the needs and alternatives for gasoline oxygenates and oxygen enhancers as well as alternative methods and costs for dealing with forest and farming wastes. Mechanisms to assure price competitiveness with FCV gasoline (or naphtha) must also be created, possibly involving governmental support in improving feedstock and processing economics.

7.3. Ethanol FCV Challenges and Solutions

This section provides details on the major issues facing ethanol FCV commercialization, together with specific solutions and their implications. These are organized by topic and issue, as follows in Exhibit 7-1. Note that the remainder of this chapter focuses on the ethanol component of a dual ethanol-gasoline fuel strategy. Refer to Chapter 6 for an assessment of the gasoline or naphtha side of this dual fuel strategy. Specific challenges that proved to be most urgently in need of additional effort are indicated in boldface type. Text sections on each potential challenge follow this table.

Exhibit 7-1: Ethanol FCV Commercialization Topics and Challenges

Topic	*Potential Challenge*
Vehicle Technology Readiness	Ethanol fuel formulations **Reformer technology readiness** On-board reformer cost Fuel additives and contamination
Adequacy of Societal Benefits	Air pollutant emissions levels Greenhouse gas emissions effects Multimedia impacts **California production effects** Energy security and diversity

(continued)

Public Health and Safety	Ingestion hazards Inhalation concerns RVP effects/flammable vapor space Invisible flame hazards Groundwater contamination
Market Development Requirements	(none unique)
Fuel Infrastructure Requirements	**Fuel availability** Transport and fueling Fueling stations Construction time Longer-term infrastructure expansion
Infrastructure Costs and Financing Requirements	Fueling station costs Reasonableness of infrastructure costs Risks of stranded investment **Business case** Infrastructure financing
User Costs and Financing Requirements	Fuel cost Interim financing
User Support Services	(none unique)

7.4. Vehicle Technology Readiness

7.4.1. Ethanol Fuel Formulation

What ethanol fuel formulations are realistic for FCV use?

A long-term all-ethanol national FCV fuel strategy appears infeasible. This study's 40,000 vehicles/year interim milestone for FCV demand levels add only about 1-3% to existing national consumption, well within available unused ethanol production capacity, but the currently mandated shift from MTBE to ethanol for ICEVfuel oxygenation purposes would require the entire current idle capacity and much more by that time. Major capacity expansion to fulfill the oxygenate requirement is already well underway in the Midwest, responding in particular to the recent US EPA denial of California's request for exemption from the oxygenate requirement. In later years, the FCV demand could be far greater. Ethanol availability would have to meet the expected national FCV demand growth until a transition to renewable-based hydrogen could reasonably be hoped to begin—perhaps 2020.

For conventional engine use, gasoline with ethanol for oxygenation or octane enhancement typically is restricted to very low ethanol concentrations. For example, in federal RFG areas the allowable range of 2-3.5% oxygenation translates into 5.7-10%

ethanol on a volumetric basis. Since CARB NO_X equations penalize higher fuel oxygen levels, most refiners will tend to hold to the low end of this volume range. If applied throughout California, this level would require as much as 800 million gallons of ethanol annually. In order of magnitude, an eventual 25% nationwide adoption of pure ethanol FCVs would require about 10 billion gallons of ethanol per year. These figures compare with present nationwide fuel ethanol consumption of about 1.8-2.0 billion gallons per year, primarily produced in the Midwest from grain and corn-based feedstocks. This would strain the most optimistic long-term estimates of available biomass feedstocks, including those available in California, as well as acreage for energy crops nationwide.

Both all-ethanol (denatured) and ethanol-gasoline blends are possible, as noted in the proposed ethanol strategy. Since ethanol at lower blend levels (i.e., below 40v%) increase fuel volatility and evaporative emissions, blends containing 40v% or greater would provide the greatest benefit. Here the principal difficulty is that at least 40% of all FCV fuel would have to be ethanol, which would work well through the initial sales milestone but would become increasingly difficult as FCVs became more widely used.

The ethanol supply issue leads to the study team's proposal of a different strategy, fielding both ethanol and gasoline as parallel and complementary fuels rather than blends. This approach gives maximum flexibility both with respect to ethanol supply limitations and the preferences of fuel retailers as to which fuel may be offered at each station.

7.4.2. Reformer Technology Readiness

Can appropriate on-board reformers be developed soon enough to avoid FCV commercialization delay?

Ethanol shares this issue with gasoline, since essentially the same reformer technology will be used for both. This reformer is a major uncertainty, with some observers believing that a practical sulfur-tolerant gasoline/ethanol ("multi-fuel") reformer cannot be developed and others arguing just as strongly for its need and inevitability. Judgment of this issue is beyond this study; here the difficulty and skepticism are noted but it is assumed that the reformer will be developed. If this development is slowed and other elements of FCV commercialization proceed more quickly, this could easily delay market introduction.

At the same time, this study considers the alternative of a somewhat simpler alternative multi-fuel reformer that requires fuels with near-zero sulfur and aromatics, thus enabling use of naphtha as well as ethanol that has been denatured with sulfur-free or very low-sulfur components (e.g., more naphtha). Such a reformer could be more reliable and less costly than a gasoline/multifuel reformer that must avoid coking over a wide range of different gasoline constituents, each with different boiling points, catalyst activities, and propensities to coke. The fuel industry may elect to pursue this alternative, either for an all-naphtha approach or for this type of ethanol/naphtha supply.

7.4.3. On-Board Reformer Cost

What are the overall cost implications of on-board ethanol reforming?

The reformer costs would be similar to those in an all-gasoline fuel strategy, since the reformer is almost the same. The gasoline/multifuel reformer technology that could be available for the pilot phase may not be adequately cost-effective for mass-market use until several years of further refinement and volume production. However, due to the relatively small volumes of vehicles to be built during the pilot phase, the total excess cost may be reasonable for either government support or manufacturer forward pricing, assuming that the reformer production cost soon declines with experience and volume.

A cost scenario similar to that outlined for gasoline in Chapter 6 provides perspective: A $5000 initial reformer cost premium on 3000 early FCVs would result in a total premium of $15 million (alternatively, about $600 per year for the life of the vehicle or about $3 per conventional gasoline gallon-equivalent over an assumed 8-year vehicle life at 75 mpg-equivalent). However, if more economically built reformers were then to appear and the earlier excess cost amortized over the next 100,000 FCVs, the cost premium per vehicle would be only $150 or less than $20 per year. Alternatively, if allocated to the fuel used by those 100,000 vehicles over an 8-year period, the premium would be about $0.09 per gallon-equivalent.

Note that this analysis assumes that the automaker is ultimately able to produce FCVs at acceptable market prices including the cost of the reformer. This will be a substantial challenge for all liquid fuel FCVs, and particularly for the relatively complex gasoline or ethanol/ gasoline multi-fuel reformer. Judgment of this likelihood is beyond the scope of this infrastructure-oriented study.

7.4.4. Ethanol and Gasoline/Naphtha Additives and Contaminants

Are there additives and contaminants that require further mitigations for practical use in reformers?

California Phase III RFG ethanol is limited to 10-ppm sulfur, although many ethanol plants can readily limit sulfur to ~1ppm. The wet mill process can yield 1-2ppm sulfur. If the product is denatured at the minimum level of 2v% with low sulfur gasoline (30ppm), this would add 0.6% sulfur. If higher levels of denaturing or other sulfur sources appear, and reformers tolerating such sulfur levels are not developed, it will be necessary for the sulfur content of ethanol to be further reduced. This may require special monitoring of the ethanol production process and selection of sulfur-free components for denaturing. Such denaturants would require approval by the Bureau of Alcohol, Tobacco and Firearms. If a petroleum refinery zero-sulfur product such as naphtha were used for denaturing, it may be possible to forego the BATF approval process.

The current industry standard for fuel grade ethanol (ASTM D 4806) allows 40-ppm inorganic chloride and 0.1 mg/Kg maximum copper content. These levels should be sufficiently low to avoid problems in the reformer, but verification is needed. In addition, ethanol routinely contains corrosion inhibitors. Ethanol can be shipped with or without such additives depending on the requests of the user; FCV uses should require no such additives. If necessary a new ASTM standard for ethanol for use in fuel cell reformers could be developed.

Other uncertainties are also present. Fuel quality requirements must be identified through reformer development in order to assess the production investment and fuel price implications. A separate and incompatible refueling connector must be developed for the ethanol stations, as well as the naphtha if used in lieu of gasoline. However, neither of these is expected to pose insurmountable challenges if addressed soon. A greater concern is in the possibility of fuel contamination through shipment of the naphtha (or clean gasoline) through existing multi-use pipelines, which could be capable of transferring sulfur from other products into the low-sulfur FCV fuels. If this problem does occur, fuel cleanup would be required at the terminal or fueling station. This possibility, only recently raised by the US DOE, requires further study.

7.5. Adequacy of the Ethanol Option's Societal Benefits

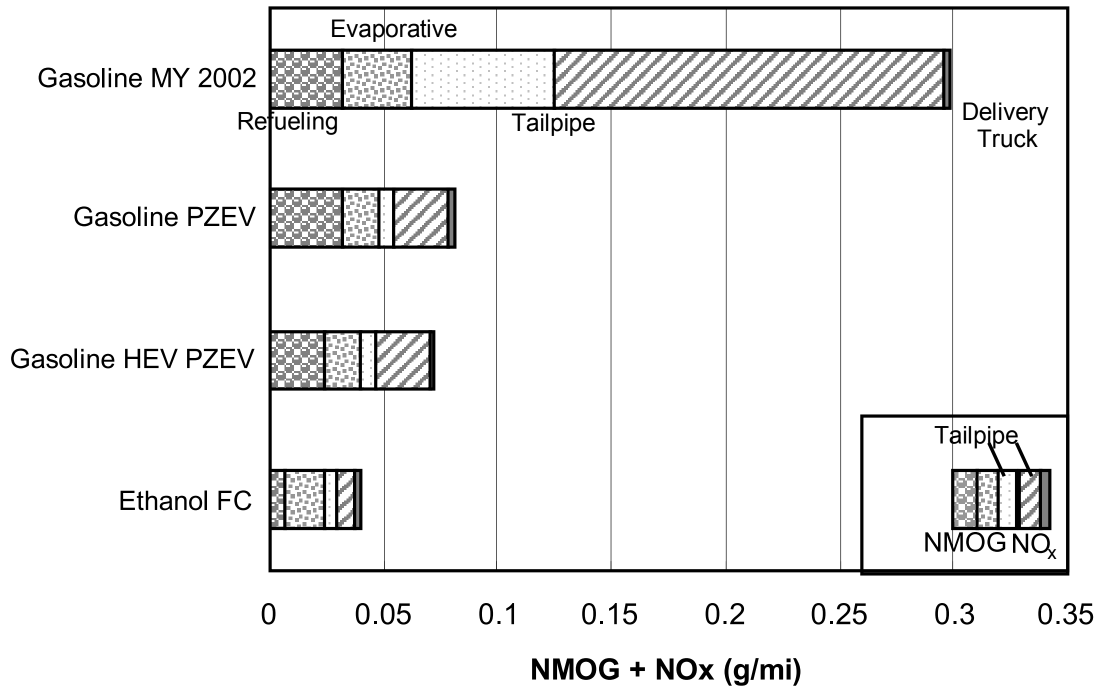
The environmental impacts of ethanol can be advantageous, but depend substantially on ethanol's share of the market in parallel with gasoline or naphtha. Ethanol's low RVP is associated with reduced evaporative emissions, although in some gasoline blends (~3-40% ethanol) the blend RVP is actually higher than that of straight gasoline. Such blends are routinely avoided for ICEV use. Ethanol's use of biomass feedstocks results in very low GHG emissions. However, its use in a dual-fuel ethanol/gasoline strategy as suggested in this study leads to a more complex environmental picture combining the effects of the two fuels. Finally, ethanol offers potentially valuable fuel flexibility and security possibilities.

7.5.1. Local Air Pollutant Emissions Effects

What is the expected air pollutant emissions impact of ethanol FCVs?

This study emphasizes an ethanol strategy in which the ethanol is sold only at some fueling stations, depending on relative prices, and splits the FCV market with gasoline (or naphtha) either regionally, seasonally, or within the same markets. However, since that proportion may vary widely depending on relative price and other factors, this section's environmental impacts are presented only for the ethanol portion. These may be compared and merged informally by the reviewer using the parallel graph for naphtha in Chapter 6. In that graph, for example, the naphtha FCV is estimated to produce approximately 0.04 g/mi of NMOG + NO_X, versus essentially the same amount for the ethanol FCV as shows in Exhibit 7-2.

Exhibit 7-2: Local Air Emissions of Ethanol FCV Fuel Options vs. Comparable Conventional Vehicles



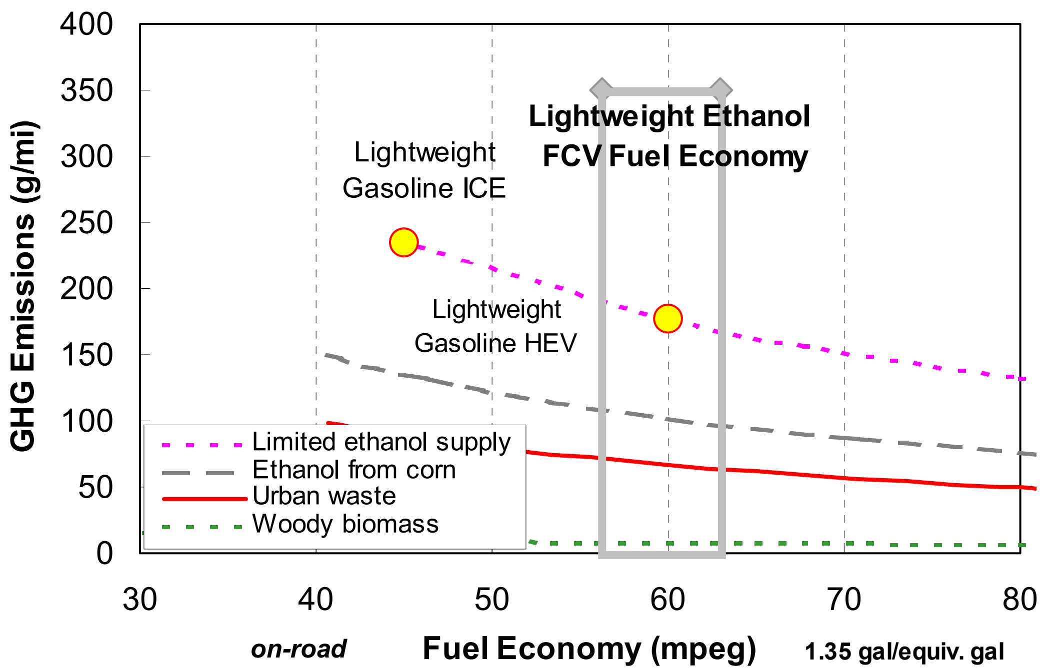
7.5.2. Greenhouse Gas Effects

What effects on emissions of greenhouse gases are ethanol FCVs expected to have?

The GHG emissions for ethanol are shown in Exhibit 7-3. For most feedstock alternatives shown, these emissions are very low compared to gasoline because only the portion of the CO_2 resulting from fossil fuel (e.g., natural gas or fossil-derived electricity used in ethanol production and transport) is counted as a greenhouse gas. In the case of forest and agricultural waste feedstocks for ethanol production, the material would produce CO_2 through natural decomposition even if unused. For corn production, the carbon in the biomass was recently removed from the atmosphere for the purpose of growing feedstock for ethanol production. The fuel economy assumptions used here are similar to those for gasoline-powered vehicles in Chapter 6.

If ethanol is used in a trade-off dual-fuel strategy as suggested in this study's proposed ethanol strategy, the GHG emissions related to that approach will vary between the estimated levels for ethanol (above) and low-RVP/low-sulfur gasoline (Chapter 6). The resulting overall GHG emissions, although varying by season and other factors affecting fuel price and availability, will still be superior to those of conventional vehicles.

Exhibit 7-3: GHGs for Ethanol FCV fuel options vs. ICEV & HEV



7.5.3. Multimedia Environmental Impacts

Will ethanol FCV fuels have "multimedia" (soil and water) impacts requiring further effort in understanding, regulation, and/or mitigation?

Like methanol, ethanol is water soluble and biodegradable. This would seem to favor these fuels in terms of underground leaks as well as open spills from tanker ships and trucks. However, what happens with alcohols in underground leaks remains an open issue. Leaking gasoline tanks in Lake Tahoe have highlighted the issue of non-gasoline components in underground leaks. MTBE has been found in ground water from leaking gasoline tanks. When MTBE was replaced with ethanol, without repairing the tanks, ethanol also began to appear in ground water. The fate of these oxygenated compounds is being researched by several agencies and summary information will be available in the near future.

Because of the attractive economics of vending ethanol from existing gasoline stations, it is more than remotely possible that some ethanol might eventually leak from tanks into soil already contaminated with gasoline from an earlier leak. The contaminants are benzene, toluene, and xylene (BTX) toxics from gasoline leaks or spills, either as prior occurrences or from the spillage of ethanol-gasoline blends. If the ethanol significantly extends the mobility of the toxic BTX plumes from the gasoline, it could exacerbate already-confirmed serious health dangers to water sources.

When ethanol is present with BTX components the microbes in the soil preferentially degrade the alcohol. Thus until the ethanol presence is eliminated the BTX components are not being biodegraded at as fast a pace. While this has not been a major concern for 10v% ethanol blends, there are no completed field studies on the impact of higher-level blends or pure ethanol on the biodegradation of BTX.

An extensive modeling study was done on this issue for the Governors' Ethanol Coalition as a part of a comprehensive environmental fates analysis for ethanol (Ulrich, 1999). That study predicted that ethanol would extend BTX plumes by no more than 25%, but emphasized that field verification is needed. This topic may therefore require further experimental research soon on the degree of danger and risks of exposure. This study team's recommendation is to follow the current experimental efforts (on methanol) closely and replicate those with ethanol and gasoline blends as needed to assure timely closure--needed as soon as possible so that ethanol can be given serious consideration in time for both the pilot phase and early market introduction.

7.5.4. California Ethanol Production Effects

What impacts will the production of ethanol in California have on air emissions?

Potential future ethanol production in California would have significant emission benefits. Ethanol produced in California from cellulosic biomass residues will reduce local air pollution due to reduced agricultural open burning, reduced risk of catastrophic wildfires, and fewer prescribed forest burns. These were findings of a recent report by the CEC (2001) on costs and benefits of California ethanol production. Under a scenario of 200 million gallons of ethanol production per year, over 1000 tons of NMOG and NO_X emissions are reduced when agricultural and forest residues are converted to ethanol rather than burned off. However, these benefits cannot be attributable to ethanol FCVs due to recent regulatory actions involving ethanol use in conventional vehicles.[13]

7.5.5. Energy Security and Diversity

Of all FCV fuel options, ethanol may provide the most positive impacts on both energy security and diversity. It is anticipated that all ethanol will be produced domestically, resulting in a major long-term decrease in foreign petroleum dependence. In addition, the feedstocks are various forms of biomass not otherwise utilized, rather than diversion or additional use of any existing energy source. This is a unique and significant step in national energy diversification.

---

[13] As of June 2001, the federal government's rejection of California's request for waiver of the upcoming national requirements for oxygenate use, coupled with the state's earlier decision to stop the use of MTBE, results in a near-term future statewide requirement for ethanol that will be far in excess of likely in-state feedstock access and production expansion capability. This implies that the air emissions benefits of any in-state ethanol production will be attributable only to the use of the conventional gasoline for which the ethanol is required, rather than any FCV use.

7.6. Public Health and Safety Requirements

Concerns considered here include ethanol ingestion, flammable vapor space creation, flame invisibility, ingestion of ethanol/BTX-contaminated water, and inhalation of ethanol fumes during refueling.

7.6.1. Ethanol Ingestion Concerns

Are further measures needed for protection against ethanol ingestion?

Ingestion and associated problems of intoxication, resulting health and safety risks, liquor tax, etc. are also often raised for alcohol fuels, but BATF regulations have long required ethanol to be denatured effectively at the production plant before it can be shipped. The specific requirement is for min 2%/max 5% gasoline or other approved denaturant that is provably effective in deterring ingestion. Bitterant and colorant agents other than gasoline could be effective in very small concentrations (~1-5ppm), but available agents are organic and feared to contaminate on-board reformer catalysts. It is concluded in this study that no additional safeguards beyond routine denaturing with gasoline or naphtha should be needed.

If, instead of gasoline, a special naphtha-like fuel is required by the reformer, then that blending component will need to be tested and approved by the BATF to assure similar effectiveness in making ethanol unpalatable.

7.6.2. Ethanol Inhalation Hazards

Does inhalation of ethanol fumes during refueling with ethanol-gasoline blends pose a health threat?

This is not a danger new with FCVs, since extensive experience has been gained with similar refueling of ICEVs using gasohol and other ethanol-gasoline blends. The Ulrich study cited above also concluded that no significant health threat is posed by ethanol fumes in the concentrations and exposure times found during refueling.

7.6.3. Flammable Vapor Space Hazards

Will ethanol’s low RVP result in a need for special measures to protect against fire or explosion arising from a flammable vapor space in fuel storage on-board the vehicle and throughout the supply chain?

Flammable vapor space in storage tanks throughout the ethanol supply chain, including on-board the vehicle, may be a possible source of fire or explosion dangers due to the low RVP of pure ethanol and ethanol-dominant gasoline blends compared to that of gasoline and some low-ethanol blends. This ignition risk associated with ethanol's flammable vapor space is often cited as an issue, but the use of fuel tank flame arrestors has been routine for many years worldwide on millions of flexible fuel and dedicated E85 vehicles as well as in fuel transporters and stationary tanks. The principal further effort now recommended for near-pure ethanol as well as any other low-RVP fuels is the formation of an industry committee to review current FFV mitigation approaches and confirm their adequacy. No further research should be needed.

7.6.4. Invisible Flame Hazards

Will ethanol's invisible flame require safety measures beyond current standard practice in the methanol community?

Flame invisibility in daylight is an attribute of pure alcohols. However, the current BATF-required denaturants contain hydrocarbons which burn with visible flames. Fuel grade ethanol burns with a faintly visible flame in daylight. This study found no evidence of inadequate flame visibility in fuel ethanol accidents or other ethanol fires. However, if other denaturants are required for fuel cell use, flame invisibility could become an issue for personal safety among emergency response personnel as well as users and the public at large. This should be addressed through early testing and further development of denaturants as needed.

7.6.5. Groundwater Contamination Concerns

Do health risks from potable groundwater contamination due to ethanol require further study or mitigation?

Ingestion of contaminated water has been suggested as a possible danger for ethanol as well as methanol. Ingestion of benzene, toluene and xylene (BTX) are recognized health dangers. See the Environmental Impacts section above for an outline of how gasoline-source BTX might be moved into groundwater by ethanol, along with suggested actions. This is expected to be only a small risk but important to resolve as soon as possible.

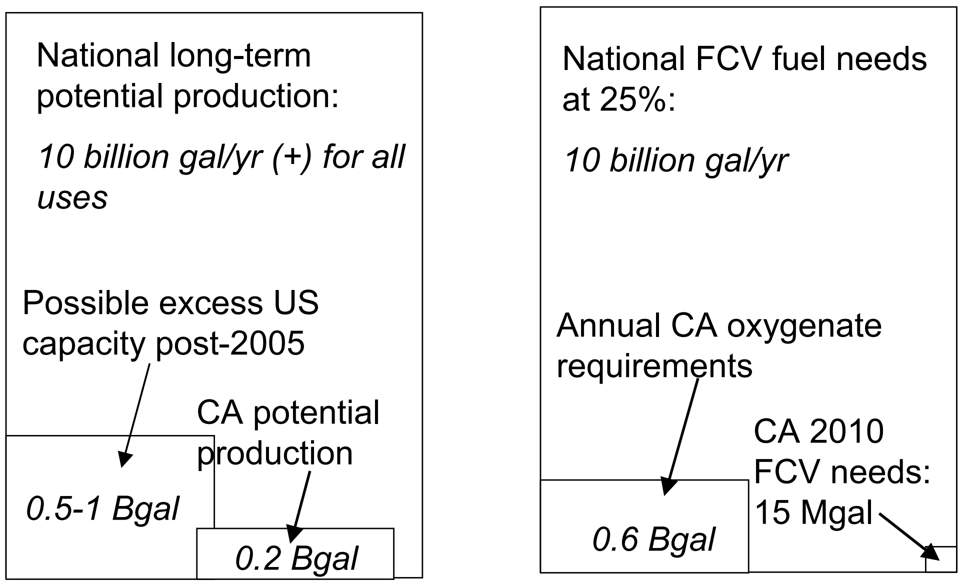
7.7. Ethanol Infrastructure Requirements

7.7.1. Adequacy of Ethanol Supply

Will there be enough ethanol at acceptable prices for its use as a primary FCV fuel—both for early market introduction in California and later nationally?

This study's specified 40,000 vehicle/year milestone implies an FCV population of about 75,000 at that point, using some 15,000,000 gallons of fuel at an assumed 60 mpg and 12,000 mi/yr. At that point annual growth in FCV use is expected to be rapid, and may require at least 10,000,000 gallons *more* each year. However, in perspective, California's annual oxygenate requirement is estimated at some 600,000,000 gallons of ethanol (Downstream, 1999), so the state's total fuel ethanol demand will be many times higher than the FCV use, as shown in Exhibit 7-4.

Exhibit 7-4: Ethanol Production Capacities vs. Projected Uses



While there are many high-volume sources of biomass feedstocks in California, not all of these are easily and economically collected and transported. A new CEC study of ethanol production capacity and costs in California (CEC, 2001) and its earlier companion study (CEC, 1999) indicate that the maximum practical California production capacity from biomass may be only 200,000,000 gallons/year using a combination of forest waste material, agricultural residues (notably rice straw) and selected urban wastes. All of this would be used first in meeting the new California fuel oxygenate requirements with ethanol. Expansion beyond this level may require improved biomass collection techniques or the planting and harvesting of energy crops such as switch grass.

However, within the coming decade Midwest ethanol plants are expected to develop substantial excess capacity due to the current rapid growth in capacity for oxygenate requirements that is predicted to be followed soon by a gradual decline in demand as more US urban areas become ozone-compliant. This excess capacity in the Midwest plus small amounts of imported ethanol capacity are estimated to provide a potential annual delivery capacity of some 500 million gallons for FCV use by 2005-2010. This amount of ethanol could be augmented through diversion of some of the 750 million gallons otherwise sold in the lower-valued octane enhancement markets in Midwestern states (Downstream, 1999). This suggests that ample ethanol could be provided for California's oxygenate and FCV needs far beyond early market introduction, even though the state's own production capacity may not be sufficient by that time.

Despite adequate ethanol availability for California needs, ethanol prices and their competitiveness are difficult to predict. In the current transportation fuels market, ethanol enjoys a $0.54/gallon federal tax credit that keeps it competitive with gasoline. For example, the rack price of gasoline in Los Angeles as this paragraph was written was $1.17 while ethanol net of its tax credit was $0.89. Projected mid-decade terminal prices for the out-of-state ethanol are in the $1.05-1.15/gallon range (Downstream). The CEC 2001 report acknowledges that California-produced ethanol may not be price-competitive without substantial state incentives.

The California market cannot be considered in isolation. The FCV market will develop only slightly later in the remainder of the country and elsewhere, dramatically increasing FCV fuel requirements. A 25% national FCV market penetration would require some 10 billion gallons/year of ethanol, which is the entire US ethanol production capacity identified as a long-term stretch goal by US DOE. This suggests that ethanol might be used as a primary fuel in the introductory period, depending on price as well as competing uses, but would eventually have to shift to a combined ethanol-gasoline blend or mix of parallel ethanol and gasoline fuels.

7.7.2. Ethanol Transport and Station Requirements

What are the physical requirements for ethanol or ethanol-gasoline transport and fueling stations?

The delivery of ethanol fuel or ethanol-gasoline blends appears to pose no unique difficulties. A small ethanol industry already exists in California, with a current production of 6.8 million gallons per year, and substantial volume is also imported. The infrastructure for ethanol is already in place down to the terminal level. Ethanol is already being shipped by both sea and rail to California and then trucked to terminals. Only incremental expansions are needed as FCV fuel requirements grow.

As with methanol and naphtha-like FCV fuels, existing gasoline stations can be used, and either a new underground tank can be added or the mid-grade gasoline can be supplied through blending of regular and high-octane fuels and its tank converted to ethanol use by adding an internal liner and new piping.

7.8. Ethanol FCV Market Development

There appear to be no significant unique aspects, either positive or negative, to the ethanol strategy's market development opportunities and needs. The use of a dual-fuel strategy may help to minimize fuel prices, but should be essentially transparent to the typical user, who will use the two fuels (and sometimes a blend) interchangeably and possibly from the same pump. Warnings concerning the dangers of (denatured) ethanol ingestion will need to be a part of the public education effort for FCVs. Some marketing advantages may derive from the environmental image of ethanol's use of biomass feedstocks. However, there appears to be no need for significant changes from the market development approach in Chapter 3.

7.9. Ethanol Fueling Infrastructure Costs and Financing

Since the limited output of any new California ethanol plants using forest and agricultural waste would be necessarily dedicated to the state's ICEV oxygenate needs, the cost of such facilities is not relevant to FCV fuel infrastructure. As shown earlier, EFCVs could rely on a combination of Midwest ethanol from existing producers and gasoline or naphtha from existing California refineries well beyond the 40,000 vehicles/year point.

In this study's proposed joint ethanol-gasoline strategy, the dominant gasoline / naphtha component must also be considered in addition to ethanol production. Conventional gasoline will require no special production costs or financing needs. If a special fuel such as naphtha is required for the reformer, some limited refinery modifications will be needed. This study's review (Appendix F) indicates that those costs will not be major. They can be financed by the fuel producer, aided if needed by governmental backing of fuel prices and possible backing of downside take-or-pay agreements.

At the assumed 10% ethanol level, delivery arrangements will involve very low volumes of fuel through the 40,000 vehicles/year milestone (i.e., 3 trucks/day). These costs can be financed fully through the fuel price and require no special arrangements.

7.9.1. Fueling Station Cost

Fueling station costs are assumed to be the same as those estimated for methanol and naphtha, since the naphtha and ethanol stations are interchangeable: For this study this yielded an average estimated cost of approximately $60,000 per station including a mix of new tanks, relining, and diversion of existing alcohol-compatible tanks. This cost also includes piping, dispenser, signaling and controls, and related island and traffic flow modifications.

The ethanol option may or may not require additional upstream investment for a California ethanol production capability. This study assumes that any such new industry would have economics no worse than those of current Midwest producers plus current interstate shipping costs. The alternative is to import the ethanol from producers in other states. In both cases, there is no need to estimate the upstream infrastructure cost, since it can more readily be incorporated into an estimated unit price for the ethanol including its known wholesale and shipment costs.

This cost buildup is shown in Exhibit 7-5, based on estimated component costs and retail per-mile price parity with gasoline for HEVs. Under the scenario represented here with retail gasoline at $1.74/gal, the required retail price of ethanol would be about $1.36 per gallon, which results in a bulk fuel ethanol price of $1.00 per gallon. The current tax credit for ethanol (for dedicated vehicles) is valued at about $0.35/gallon, so a $1.00/gallon ex-plant ethanol price would net the producer about $1.35/gallon. While this is lower than current prices for ethanol, historically the prices of ethanol have been even lower. If gasoline prices were higher, ethanol would be more attractive.

Exhibit 7-5: Fuel Cell Ethanol Fuel Parameters

Parameter	*Value*	*Unit*
Gasoline subcompact Fuel Efficiency (FE)	45	mpg
Benchmark competition HEV	56.25	mpg
Benchmark HEV Energy Efficiency Ratio (EER)	1.25	Btu/Btu
FCV EER	1.39	Btu/Btu
FCV FE	46.5	mpg
Retail gasoline price	1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Gasoline-equivalent ethanol price target	**1.42**	**$**
Wholesale ethanol price	1.35	$
Federal tax credit for small producers	- 0.42	$
Bulk fuel storage terminal	0.02	$
Truck transport	0.05	$
Federal tax	0.123	$
CA excise tax	0.12	$
CA sales tax	0.09	$
Retail ethanol residual for capital cost & margin	**0.08**	**$**

Effect of taxes: The fuel-pricing estimate includes a derived residual amount of $0.042/gallon to contribute to coverage of operating expenses. Without the assumed federal credit and reduced California excise tax, and with the retail price assumed to be unchanged, the retail residual becomes negative (-0.14/gallon). This inability to cover all costs indicates a fundamental price problem and a long-term requirement for external price support. This in turn suggests that ethanol may not be viable except as an addition to the gasoline/ naphtha strategy to provide partial insurance against extreme gasoline price increases.

7.9.2. Infrastructure Cost in Context

What are the costs of the ethanol FCV fueling infrastructure relative to the fuel costs of the FCV user and the conventional ICEV owner?

Since the costs of this ethanol infrastructure are similar to those of naphtha and methanol, the same perspectives can be applied to put those costs into a broader perspective. The naphtha cost context is described in Chapter 6, and is the dominant element in this dual-fuel ethanol strategy. Ethanol's infrastructure involves little if any cost increment beyond that of naphtha installations. Ethanol's high fuel cost, under current and anticipated conditions, would result in its use in no stations (and therefore no costs) unless and until its price disadvantage were reversed. This could occur with either gasoline price increases (for example due to excess international demand) and/or ethanol cost decreases due to an oversupply. In such instances ethanol could become important in not only reducing user costs but also in improved environmental performance arising from its biomass sources.

7.9.3. Stranded Investment Risk

How great is the risk of stranded EFCV fuel infrastructure investment?

The risk of stranded investment specifically for ethanol stations appears low since relatively few stations need be built initially for ethanol; the remainder would be built primarily for naphtha use but could be converted to ethanol as needed. Most of the new ethanol station infrastructure could be converted if either a dedicated naphtha or methanol strategy later proved superior either for FCVs or alternative-fuel ICEVs. However, if conventional gasoline were to supplant ethanol for FCVs, much of the parallel ethanol infrastructure would be surplus to the gasoline requirement and therefore a stranded cost. A risk premium may thus be applied by potential ethanol infrastructure investors, depending on their assessments of this risk based on gasoline FCV technology development at the time of the investment decision.

7.9.4. Adequacy of Business Case

What is the business case for investment in EFCV fueling infrastructure?

Even if the investment capital requirement appears relatively small for the first-decade ethanol station infrastructure, a business case must be demonstrated for such a commitment. This study modeled the financial implications of the required capital and operating cost investment amounts and timing, continuing beyond the 40,000 v/yr market milestone point, versus the rates and timing of the revenue stream anticipated for the market development scenarios used. This cost model and its assumptions are described in Appendix E**.**

For the ethanol fraction of a joint ethanol/naphtha strategy, the results of this analysis are shown in Exhibits 7-5 through 7-8. Ethanol is represented as a hybrid strategy that allows the use of ethanol, depending on relative prices, at fueling stations that would normally sell fuel cell gasoline (or naphtha). For modeling purposes, only 50 ethanol stations were assumed since ethanol availability is expected to be limited. The remaining 450 initial stations were assumed to vend gasoline or naphtha. However, in practice all FCV fuel providers could have the capability and opportunity to sell ethanol when market conditions are favorable.

A key issue governing the use of ethanol in FCVs is its alternative use as a blending component to gasoline. With the recent MTBE phaseout in California, ethanol will be in high demand and may not be available at low prices. The example illustrated here shows a very low retail margin for ethanol. The advantage of ethanol, however, is that the fuel provider can switch between ethanol and naphtha depending upon market conditions.

Exhibit 7-5: Ethanol Fueling Station Cost Components (50 ethanol stations)

Costs through year 7	*Value($000)*	
Capital investment for initial 50 stations	$3,500	
Net negative cash flow plus capital investment through year 7	$7,825	(40,000v/yr)
Net Present Value, $000	$5,369	

Note that in the following Exhibits 7-6 (annual cash flow) and 7-8 (cumulative) the cash flow for ethanol appears small. This is due to scaling to only 50 stations rather than 500 as shown in Exhibit 7-7, thus covering only the naphtha component of the ethanol strategy. The point here is that a 10% ethanol station component would have little impact on the costs of the overall strategy, and in any event could be no different from those of the remaining (assumed naphtha) stations required.

Exhibit 7-6: Ethanol Fueling Infrastructure Cost and Revenue Projections

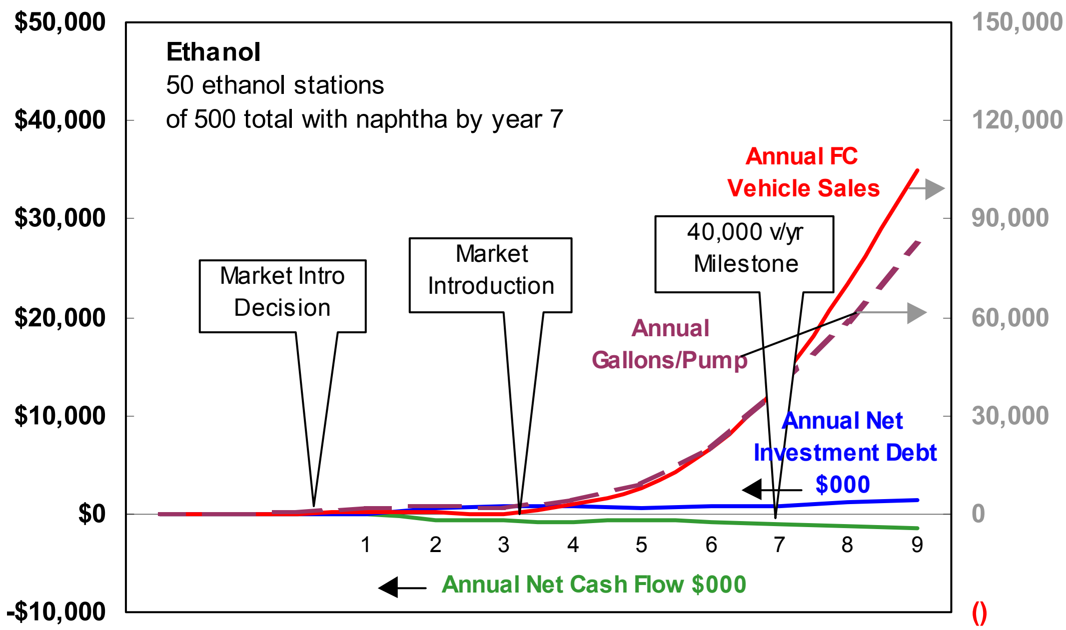


Exhibit 7-7: Parallel Naphtha Infrastructure Financial Performance

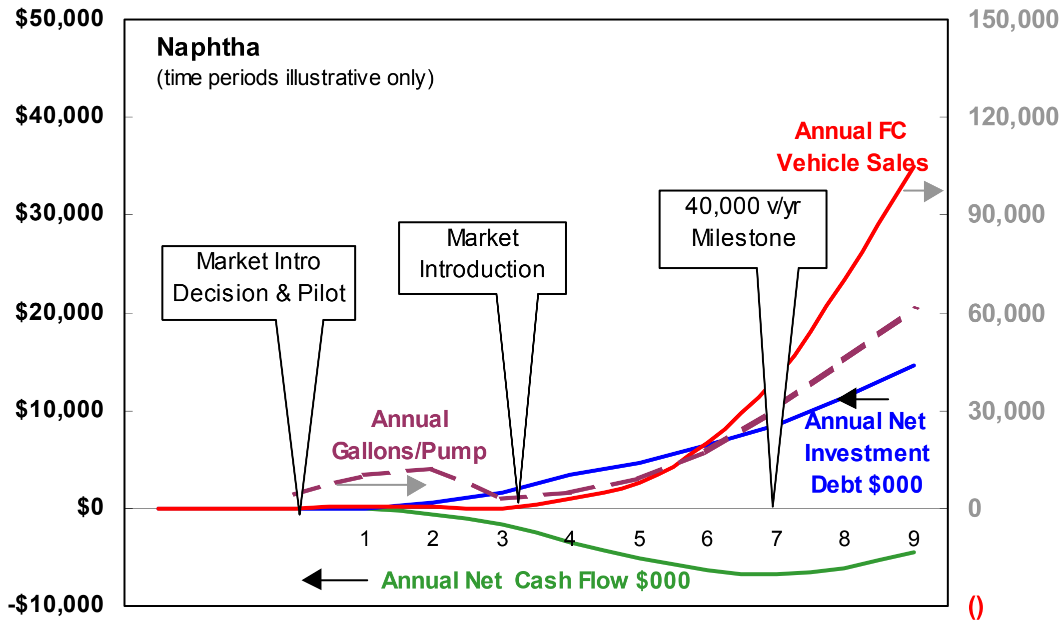
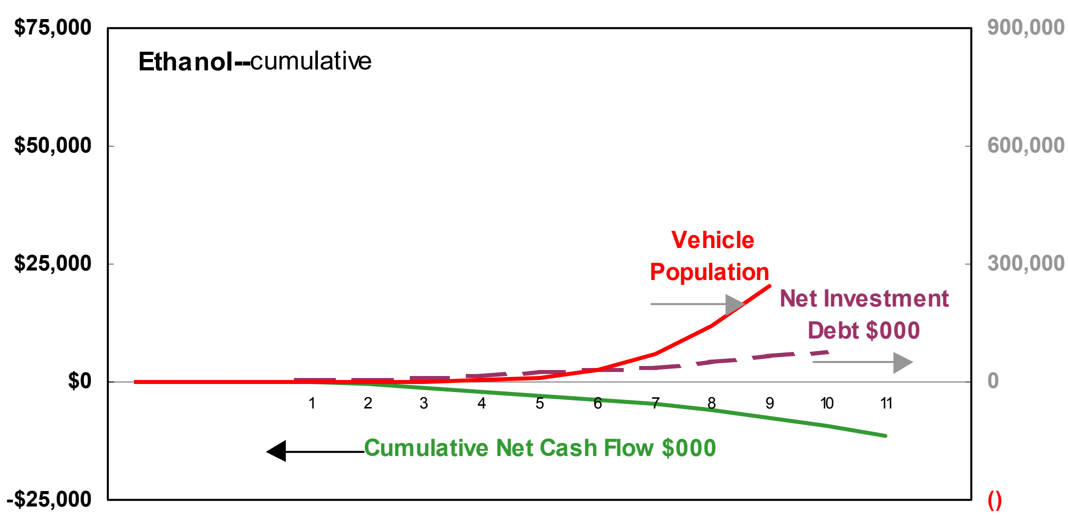


Exhibit 7-8: Cumulative Cash Flow for Ethanol Infrastructure (50 stations only)



7.9.5. Ethanol Infrastructure Financing

How can the required ethanol infrastructure investment be financed?

It is feasible to form investment consortia to share this financial investment risk and its potential returns, but may be unnecessary due to the scale of these initial costs. This is similar to the financial outlook for the other liquid fuels. However, as for other fuels, the implications of a broader FCV introduction are more financially strenuous.

The investment in a national ethanol FCV fuel infrastructure gains little if any economy of scale or experience from the California start, so the infrastructure cost for the nation would be proportional to the relative number of fueling stations or about ten times that required for California. This investment would follow a trajectory similar to that in California, first to equip the assumed minimal introductory 5% of all fueling stations and then to expand the ethanol capability gradually to more stations. As with the other liquid fuels, this expansion requires major financial commitments both for the initial national rollouts and then for the expansion of the infrastructure in California and elsewhere as demand grows. The capital investment required for station development is unchanged from the naphtha case as presented in Chapter 6. However, under this study's assumptions of future cost parameters the net negative cash flow per station is substantially increased due to the high cost of the ethanol. This ethanol strategy, therefore, can only be used as a hedge against the risk of unexpectedly large increases in gasoline prices (and/or ethanol cost declines), when it would become economic to switch as many stations as possible to ethanol for FCVs.

7.10. Ethanol FCV User Costs

As with other FCV fuel choices, user costs are sensitive to fuel price fluctuations. User perceptions of their costs may be even more sensitive to such variations in the prices they pay for fuel. The dual-fuel ethanol/gasoline strategy as suggested here is intended to minimize both the fuel price and its variations by providing two fuels that can either be substituted or blended for best use of the most economical fuel at any time.

Current stable ethanol prices of approximately $1.50 per gallon at local terminals suggests that even with taxes and all retail delivery chain costs added, the fuel may be close to price-competitive with conventional gasoline on a per-mile basis. To establish and keep the ethanol price reliably at or below that of gasoline, however, will require futures price contracts as described in Chapter 3 and/or governmental support of the price parity through a system of analytically derived baseline vs. ethanol FCV fuel economy. This is somewhat complicated by the use of a joint ethanol-gasoline strategy; this study concludes that early research is needed into the options for such a system design, building on similar efforts for earlier alternative fuel vehicles.

7.11. Ethanol FCV User Support Services

This study found no unique needs of ethanol or the ethanol/gasoline dual-fuel approach in the provision of user support services such as insurance, maintenance, repair, and emergency response. See Chapter 3 and the other alternative fuel assessment chapters for further details.

7.12. Selected References for Ethanol FCV Issues

Armstrong, Sarah R., 1999. *Ethanol: Brief Report on its Use in Gasoline*, by Cambridge Environmental Inc. for the Renewable Fuels Association

California Energy Commission. *Costs and Benefits of a Biomass-to-Ethanol Production Industry in California,* Draft Report P500-01-002, dated March 2001, by Arthur D. Little, Inc. www.energy.ca.gov.

California Energy Commission, December 1999. *Evaluation of Biomass-to-Ethanol Fuel Potential in California,* Report P500-99-022.

Lynd, Lee R., 1996. Overview and Evaluation of Fuel Ethanol from Cellulosic Biomass: Technology, Economics, the Environment, and Policy. Dartmouth College, Thayer School of Engineering.

Glassner, D., J. Hettenhaus, and M. Schechinger, 1999. Corn Stover Collection Project, presented at BioEnergy 98 Conference.

Downstream Alternatives Inc., 1999. The Use of Ethanol in California Clean Burning Gasoline, for Renewable Fuels Association.

Ulrich, Glenn, 1999. *The Fate and Transport of Ethanol Blended Gasoline in the Environment*, by Surbec-Art Environmental for the Governors' Ethanol Coalition.

United States General Accounting Office, 2000. *Petroleum and Ethanol Fuels: Tax Incentives and Related GAO Work*, informal report to Senator Tom Harkin, U.S. Senate.

U.S. Department of Energy – various ethanol program reports and synopses

Wang, M. C. Saricks and D. Santini, 1999. *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*, ANL/ESD-38, by Argonne National Laboratory for the U.S. Department of Energy.

8 Conclusions and Action Recommendations

8.1. Overview

This chapter outlines the principal conclusions of this study of alternative fuel cell vehicle fuel pathways and challenges. Also included in this section is a listing of early action recommendations derived from the study that the consultant study team believes are the most important next steps in moving forward toward fuel cell vehicle (FCV) commercialization.

8.2. Principal Conclusions of the Study

- If the vehicles and their fuel processing and fuel cell technologies are developed adequately on the required timeline, including on-board reformers and storage as needed, **all other challenges to FCV commercialization can be overcome** albeit in some cases with high cost, difficulty, and risk requiring public support.
- The four different FCV fuel technologies have positive but widely varying societal benefits, particularly in environmental effects including local emissions and greenhouse gas reductions. **In general, all FCV fuels appear able to surpass the environmental improvements of projected gasoline hybrid ICE/battery vehicles** over conventional all-ICE vehicles. FCV environmental benefits need to be presented as a pathway to long-term future societal benefits rather than early major improvements.
- **The crucial ingredient for rapid progress** is a more positive motivation for FCV developers and fuel providers to accelerate their efforts. Given the extreme uncertainties and financial risk to all, this motivation can best be provided through early and positive governmental support to reduce that risk and reward progress through mechanisms such as tax relief, stranded investment insurance, and direct public investment participation.
- **Fuel supply and infrastructure can be provided if risks are mitigated.** Risk-sharing strategies include initial government-

sponsored competitive fuel delivery contracts and consumer price supports, encouragement of interim fuel infrastructure consortia, and tax incentives for infrastructure technology development and installation. Carmakers may need to join with fuels suppliers in forming initial fueling infrastructure partnerships, including both government and private investors. In addition to financing, there will be logistical difficulties due to the sheer number of stations to be equipped rapidly enough to keep pace with market demand—initially for geographic coverage and later for refueling capacity. It may be necessary to slow the pace of station density improvement in order to install more dispenser capacity at already equipped stations.

- **Development of an adequate early market demand for FCVs** to reach and exceed the study's early 40,000 and 100,000 vehicle/year California milestones can occur only with extraordinary effort. Despite potential unique value-added FCV features, little if any early price premium opportunities can be expected, particularly since lack of model variety could restrict the market. Possible solution components include the earliest possible introduction of vehicle choices to meet a variety of user preferences, a portfolio of user cost and convenience incentives, extensive consumer education and conditioning, successful pre-introduction demonstrations, supportive media reportage, and adequate infrastructure.
- **Any major pilot phase to demonstrate FCV technology should focus on commercial and governmental fleets.** Efforts to identify appropriate fleets and their concentrations in specific urban areas must begin at least two years before any industry pilot test of 1000 FCVs (the hypothetical scenario specified for this study) can begin. Based on past alternative fuel vehicle experience, Sacramento is unlikely to be able to absorb 1000 FCVs into light-duty auto fleets and other special groups quickly—including fleets of the state and local governments. At least some of this pilot test must therefore be located in the SF Bay Area, San Diego, or metropolitan Los Angeles area. Local permitting officials will also need assistance in expediting the needed infrastructure.
- **Key technical standards development activities will need to be monitored and encouraged.** Resolution of some public safety issues will require refinements in recognized codes and standards. National and international standards-setting organizations are working diligently to assure public safety and accommodate the introduction of fuel cell technology as well as the use of specific alternative fuels. For many good reasons, these efforts can be difficult and slow. FCV developers will need to monitor those efforts and augment their participation and assistance as required to minimize avoidable delays.

8.3. Fuel-Specific Conclusions

8.3.1. Key Challenges and Solutions for the Hydrogen Fuel Cell Vehicle

The on-board hydrogen-carrying FCV carries substantial advantages, notably in its generally superior long-term environmental performance, mechanical simplicity, and lighter weight. It also faces a variety of unique challenges in cost, on-board fuel storage, fuel supply, perceived safety, and regulatory challenges. The most critical challenges identified in this study include the following:

- Present development trends in both central hydrogen production systems and local station-site production alternatives such as electrolysis and steam reforming **will need improved technology** to produce hydrogen at the assumed costs during this decade. A pressing need is a low cost fuel compressor/storage system built on a large scale. A related need is for a low-cost packaged hydrogen generation system. These should be in place before FCV market introduction, requiring an early start even under the most optimistic development and deployment scenarios.

- Meanwhile a variety of **less economical hydrogen fuel supply methods will be used** while vehicle volumes are relatively low. Almost all hydrogen is currently made by reforming natural gas at large central plants. This hydrogen can be compressed and stored in tube trailers (a costly option suitable only for introductory use) for delivery to the fueling site, or liquefied and delivered by cryogenic tanker truck. Other and more promising solutions include station-site hydrogen production via electrolysis of water or reforming of natural gas with existing technologies such as small-scale partial oxidation or autothermal reforming.

- During this transitional period of the first several years, fuel sales will be in low volumes so costs per vehicle and station will be high. **Mechanisms for infrastructure and/or fuel price writedowns** will be needed for hydrogen, and will almost certainly require at least short-term incentives and regulatory support.

- The **superior long-term environmental advantages of hydrogen** will help to justify substantial government incentives and related regulatory support for such interim supplier and consumer cost writedowns. Those temporary writedowns will be needed, since the higher short term operating costs will serve as a disincentive for investors to provide fuel without risk reductions such as contractual arrangements with the government or vehicle manufacturers.

- Pressurized **hydrogen refueling technology** has already been shown to be practical and safe. Present industry efforts to standardize fueling connectors improve user convenience are expected to continue and will meet this need in time without higher-priority support. But there must be an extensive education effort to reassure the public of hydrogen's safety.

- **A combined "energy station" concept shows promise** for reducing hydrogen fueling costs, merging stationary electric power needs with FCV hydrogen demand through combining a stationary fuel cell with hydrogen production through reformer or electrolysis at potential refueling sites including conventional fueling stations, homes, places of work and shopping centers. Site-specific economic analyses are needed as well as further development, downsizing, and cost reductions in fuel cell and hydrogen-generation technology.
- **On-board hydrogen fuel storage** initially will most likely be in the form of high-pressure gas rather than cryogenic liquid or hydrides for the early demonstration vehicles. Automotive designers will need to reconsider vehicle configurations to provide space for adequate hydrogen storage. Carbon wrapped tanks will reduce both storage volume and weight but work must continue to improve their economics and safety assurance. Furthermore, because of pressurized hydrogen's inherent fuel storage volume disadvantage, early hydrogen vehicle makers will need either to accept somewhat lower range (although well beyond EV limits) or aggressive vehicle weight reductions to get a fully competitive range.
- Efforts must begin well before a pilot phase to **educate local permitting officials** in the realities of hydrogen handling and delivery for vehicular use. Focusing first on the pilot test areas, substantial evidence of success must be shown in time to help induce automakers to move ahead into that demonstration phase.

8.3.2. Key Challenges and Solutions for the Methanol Fuel Cell Vehicle

Assuming the successful and timely development of a cost-effective on-board methanol reformer, there are several other crucial challenges to be addressed, ranging from fuel price and taxation practices to refueling infrastructure investment risks and toxicity concerns.

- The crucial concern for the methanol FCV is outside this study's scope: the timely development of a market-ready **on-board reformer**. This reformer technology appears to be advancing quickly but must be on a clear path to economic viability before the decision can be made to begin low-volume commercial production.
- The delivered price of fuel cell grade **methanol can be competitive**. This assumes production from remote natural gas with sea, rail, and

truck delivery to refueling sites. These delivery mechanisms are already available, with direct California experience for the M85 alternative fuel vehicle program of a decade ago. However, this conclusion is highly sensitive to changes in assumptions such as methanol feedstock competition.

- **Refueling infrastructure investment** is much smaller for methanol than hydrogen, but its financial risk is still a significant deterrent—particularly in view of the possibility of later breakthroughs in gasoline-type reformers for FCVs. As in the case of hydrogen, it will be necessary to develop government incentives and possibly form consortia of investors to share that financial risk.
- **Methanol toxicity and groundwater effects are potentially delaying challenges** despite indications that these risks are manageable. Some conventional fuel providers and regulators are concerned about liabilities that might arise from dispensing methanol, both with regard to groundwater contamination and direct human ingestion. Clarifying studies of these issues as well as of refueling safeguards now under development are needed soon. Public education on the actual likelihood and results of accidents should also begin well before actual market introduction.
- **Direct methanol fuel cells** are in development, and would simplify fuel cell vehicle technology by eliminating the separate on-board reformer as well as complexities such as compressed hydrogen storage. Advantages could include reduced FCV cost and improved reliability as well as reduced overall size. However, most observers agree that although this technology may emerge soon in stationary or portable power products, it is not widely expected to appear in market-ready vehicles until near or after the end of this decade. Early FCV commercialization efforts should proceed with reformer-based technology rather than delaying commercialization to await DMFCs.

8.3.3. Challenges and Solutions for the Gasoline and Naphtha Fuel Cell Vehicles

The successful commercialization of gasoline-type fuels in fuel cell vehicles will depend almost entirely on the development of a practical on-board gasoline reformer. Although its formal evaluation is beyond this study's scope, the concerns of many industry observers must be acknowledged regarding the unique difficulties faced in gasoline reformer development. This may necessitate the use of direct hydrogen or other fuel for the initial pilot phase vehicles and a later transition to gasoline. Other key challenges that must be resolved include the following:

- If gasoline is used, essentially **no special infrastructure investments** will be required unless sulfur contamination of fuel proves to be a serious problem. There would be no severe onsite fuel storage and dispensing challenges. However, it will be essential to improve conventional levels of quality control in avoiding contamination of the fuel in transit. Alternatively, onsite fuel cleanup devices or full-scale onsite gasoline reformers, hydrogen cleanup, storage, and dispensing facilities for hydrogen FCVs could be considered.

- **If naphtha or other FCV-only alternatives are necessary, they may also have benefits** of being easier to reform as well as more fire-safe. Their expected lower RVP and evaporative emissions in turn may help qualify the fuel for a partial ZEV low fuel cycle emission score similar to the methanol FCV fuel option—a significant benefit under projected California ZEV regulations although still not a full ZEV rating as hydrogen will receive. This question requires early cooperative study with CARB in order to encourage the most appropriate reformer R&D.
- Naphtha or other FCV-only gasoline substitutes would require **infrastructure investments similar to those of methanol FCVs.** New or separate gasoline tanks and pumps would be required at the local fueling station, in addition to some refinery and delivery modifications.

8.3.4. Challenges and Solutions for the Ethanol Fuel Cell Vehicle

The primary challenges to ethanol FCVs are the projected national availability of feedstocks and the cost of the fuel. These relegate ethanol to a limited role as an element of a dual-fuel ethanol/gasoline strategy. In this approach ethanol would be unused at any stations unless gasoline prices rise substantially. This, however, may be a practical approach to assuring future fuel flexibility that could be needed unexpectedly for either economic or environmental reasons. Its use requires only the adaptation of gasoline reformer technology and fuel delivery equipment to accept ethanol, at little or no incremental cost.

A significant technical challenge is the lack of an acceptable multi-fuel on-board reformer. Ethanol requires technology similar to (and simpler than) that needed for gasoline and can even use essentially the same reformer. Gasoline-type reformer development and commercialization within this decade are still in doubt among industry experts. All other challenges to ethanol commercialization are similar to those for naphtha. Key challenges to ethanol include the following:

- **The high cost of ethanol** is the principal challenge, due to the inherent process inefficiencies and transportation distances involved as well as competition for the available supply.
- **Inadequate US ethanol supply is likely** for later and more widespread FCV use. Ethanol could still be used in fuel cell vehicles with a dual fuel strategy in concert with gasoline or naphtha.

Competing high-value ethanol used as a gasoline blending component and MTBE replacement will increase already-serious fuel price pressures and make a dedicated ethanol vehicle and infrastructure a high-risk proposition. The California economy may benefit from an ethanol infrastructure's development in the state to augment or replace Midwest and foreign imports, but its production—up to California's maximum feasible feedstock supply with currently envisioned technology—would be totally consumed by high-value gasoline oxygenation use under recent federal directives.

- **Potential ethanol health and safety difficulties** requiring early resolution include potential groundwater BTX contamination, flame invisibility, and reformer fouling due to additives that may be needed to deal with other safety concerns. Early clarifying studies and refinement of standards are required.
- **The economic and environmental implications** of various ethanol fuel source pathways need to be studied in more detail, ranging from early out-of-state corn-based production and shipment to later use of California forest and agricultural wastes. Near-term biomass use may have valuable net positive environmental impacts.

8.4. Recommended Next Steps in FCV Commercialization

This section presents a summary of activities identified in this study as important for accelerating fuel cell vehicle commercialization. Both public and private sponsors could be involved. These opportunities include two general categories:

- Activities applicable to all types of FCVs (subdivided by type of activity)
- FCV commercialization activities specific to each fuel type (subdivided by fuel type)

Within each of the following subgroups, activities are presented in recommended priority order from most urgent to least.

8.4.1. Recommended Activities Applicable to All FCV Fueltypes

A. Scenario Studies and Benefits Assessments

- **Analysis of broader range of future scenarios, assumptions, and commercialization options:** This study provides a baseline set of commercialization scenarios, as well as basic sensitivity tests, but many factors in this analysis are not reliably predictable. Further study is needed to show the effects of different scenarios and assumptions on cash flow and risk management needs for the different fuel choices. Similarly, some mixed-fuel scenarios (e.g., hydrogen and methanol in parallel introductions by different automakers) could be developed to show their impacts on net infrastructure costs and risks along with possible mitigations. Alternatives to conventional light-duty FCV market introduction could also be assessed, such as use of small neighborhood FCVs, longer-term focus on fleets, integration with FC bus commercialization plans, and tie-ins with stationary FC developments.

- **Extended environmental impact assessments and implications:** This study provided a broad overview of FCV environmental impacts, estimating each fuel's effects and indicating the nature and degree of uncertainty in current data. More detailed studies of FCVs vs. conventional vehicles would be a useful extension of this work, with an emphasis on the effects of alternative assumptions and scenarios as well as the full range of present environmental impacts that could be reduced or avoided through a transition to FCVs.

- **Broader assessments of societal benefits of FCVs:** This is an important near-term study task, involving expansion of the study's initial work on identifying and scaling FCV benefits. Societal benefits of FCVs may include environmental improvements of various kinds as well as fuel flexibility and security, vehicular noise reduction, improved public health and safety, reduced fuel consumption, and conservation of other scarce materials. This study could also include efforts to scale and assign costs to new FCV risks such as rare metals price inflation and toxicity. There may also be California-specific societal benefits such as employment in the ethanol industry. Such a study could help in education of policymakers about the value of providing FCV incentives.

B. Public Policy and Incentives Development

- **Risk assessment and mitigation methods development:** Further work on risk assessment and management via practical risk-sharing mechanisms, including both private and government initiatives—covering both supply and consumer risks. Work should include a detailed assessment of available financial risk management techniques such as futures contracts and fuel-price hedging strategies that could be appropriate for FCV fuels.

- **Joint proposals for government support:** This is a natural outgrowth of policymaker education. Stakeholders must build alliances and collaborate—possibly directly with legislators—to create specific legislative proposals for ways to provide regulatory support to accelerate FCV commercialization. These could include direct financial support in various ways as well as incentives for setting attainment targets and leveling the playing field for all automakers. Both auto and fuel infrastructure needs for initial support should be included.

- **Key R&D encouragement:** This is another important way of providing government support. The immediate need is for stakeholders to identify specific R&D needs and press for government support through cost sharing, tax credits, etc. to accelerate or broaden the private R&D efforts in addition to direct funding through government research programs. The product of this effort would be specifications for each needed R&D effort, including schedules and milestones, which could then be used to gain the needed support from state and federal R&D funding authorities and legislators.

C. Regulatory Assistance and Implementation Activities

- **Monitoring and communication of codes and standards progress:** Despite the array of industry organizations and committees working on various FCV-related standards issues, these efforts can be slow and poorly coordinated among industries, resulting in potential hidden challenges to early FCV rollouts. Existing technical standards-setting groups must move aggressively to resolve various issues such as fueling connections, fuel storage limitations, and flammable vapor space mitigations. In some cases, new groups may need to be formed to deal with specific issues. To assure that all this happens, it is important to have a clearinghouse-type monitoring of all relevant committee activities, use that information to identify potential problems, and communicate status and unmet needs to all partners. This needs to begin now and be aggressive in developing contacts and getting access to status information.
- **Local permitting process assistance:** This is focused on local permitting officials, who (as shown in past California alternative-fuel introduction efforts) will often need help in coping effectively with FCV infrastructure requirements and how those needs can be met through existing and emerging standards and national codes. It could possibly include drafting of model codes. The most effective approach may be a direct-assistance effort to the permitting officials in targeted pilot-phase and early-mass market communities so that they understand how best to interpret the available codes and standards guidance and either implement or modify their own local requirements

effectively. This is a key step that, if missed, could significantly delay FCV introduction.

D. Pilot Phase Organizational Preparations

- **Fleet population characterization to identify key early candidates:** Little is known about the existing vehicle fleets, including how to find those that may be the best candidates for the pilot phase, how many FCVs they may be able to accept, their attitudes toward such programs, and who has the authority to make such decisions in each fleet. This requires some detailed data-searching and selective interviewing to build a good picture of the California fleet market for FCVs. Focus groups may be useful in addition to data mining and individual interviewing. This task should begin well before any decision to conduct a pilot phase, so that education and marketing to fleet managers can begin in time to prepare before the initial vehicles are ready.
- **Pilot phase locational assessment to identify best cities:** This follows the previous item by using the fleet data as well as information on local codes and permitting practices to find where groups of candidate fleets are located to permit possible fueling infrastructure sharing and assure cooperative efforts in getting ready for the pilot phase (and further fleet market activity later). It should begin soon after the broad fleet characterization described in the previous item.
- **Negotiation of pilot phase participation by automakers and fuel providers:** Different automakers are sure to have quite different views on pilot-phase activities and goals; they may prefer different cities, some may not want to use fleets at all, and some may be ready to field only a small number of FCVs during that phase. If any benefits of a coordinated pilot phase are to be gained, it will be necessary to approach each automaker and negotiate what degree of participation they will be willing to commit. This includes choice of target markets, fuel infrastructure sharing, joint publicity, data sharing, and many other aspects.

E. Early Market Development Planning and Implementation

- **Further study of needed fueling station locations and numbers:** This is a critical step in testing and refining this study's current infrastructure cost estimates and relating this cost to funding sources and possible amounts. This requires more detailed locational studies, assessment of GIS systems capabilities and options for locating fueling stations, and possibly some limited public opinion and behavior testing based on existing niche market fuels such as auto diesel, CNG and propane. This work needs to be done as early as possible because it will be an important input to the development of legislative initiatives to support FCV introduction.

- **Personal FCV market assessment to establish response baseline:** This is a research activity rather than a marketing and communications effort. Although actual FCV availability will not occur for several years, an important step this year or next is to begin benchmarking the present public knowledge and attitudes—fears, understanding, desires, etc.—and planning complete market development programs. The progress of those programs can then be gauged by changes in public response over time. This probably involves some panel surveys conducted annually and linked to the planning effort. Focus groups are also a valuable tool for probing the attitudes and knowledge of a range of consumers and FCV features that they would most value, as well as identifying their susceptibility to change as they learn more about future FCVs.
- **Assurance of GIS-based station locator technology in-time readiness:** The use of on-board satellite-linked Geographic Information Systems to help drivers locate FCV refueling stations is going to be very important in minimizing the number and cost of stations to be modified for FCV fueling. This activity is an early technology assessment and status monitoring effort, focused on identifying the present plans of vendors of commercial on-board GIS systems capabilities and timing. The task also includes then working to assure that the FCV refueling station-locator capabilities can be added to those systems quickly and easily as the infrastructure develops.

F. Non-Fuel Infrastructure Development

- Emergency response systems development and implementation assistance: All ongoing efforts in emergency response systems analysis and development should be monitored. Shortfalls in schedule, funding, authority, and agreement on emergency response measures should be identified and communicated to FCV stakeholders. It may be necessary to provide further assistance in the planning and funding of such capabilities so that they are in place as needed for the earliest vehicle introductions, including pilot programs.

8.4.2. Further Activities focusing on the <u>Hydrogen</u> Fuel Cell Vehicle

- Under the hydrogen scenario, on-board compressed hydrogen fuel storage will probably be used exclusively for initial FCV introduction, with lightweight carbon fiber-wrapped tanks and possibly unique vehicle configurations to minimize loss of payload space. On-board cryogenic liquid hydrogen and metal or chemical hydride storage alternatives are less convincing for this term**. Infrastructure planning by hydrogen advocates must proceed early on this assumption**, while monitoring and allowing for the possibility of breakthroughs in the other options.

- Adequate near-term compressed hydrogen fuel supply methods are available as well as unavoidable for initial use while vehicle volumes are low. These include tube trailer deliveries, electrolyzers, and steam methane reformers, all at the fueling stations. Hydrogen's more extensive long-term environmental benefits as well as reduced hydrogen fuel costs will emerge gradually as improved technologies (more economical and efficient reformers, electrolyzers linked to renewable electricity sources, metal or chemical hydride storage, etc.) become available. Such improvements are expected to play only minor roles until after this study's initial market introduction phase. **Research on those improvements must continue**, however, with existing technologies understood to be the essential start on the road to hydrogen's benefits.

- **New compressed hydrogen fuel production and delivery system technology development should begin now** to reach viable mass-market hydrogen fuel costs and minimize fuel subsidy needs. This refers specifically to more economical mass-produced integrated units for use at stations, although systems incorporating a stationary fuel cell "energy station" for combined FCV hydrogen, grid or building power, and thermal energy should also be included. This can best succeed if the current government-funded efforts are intensified and paralleled by new independent private R&D activities and investments.

- Efforts must begin at least a year before the pilot phase to **educate and assist local permitting officials** in the realities of automotive hydrogen handling and delivery, focusing first on the communities to be selected for the pilot phase. These efforts should be successful if pursued intensively. Mechanisms recommended include on-line information services, a circuit-rider system for education and hands-on advisory assistance, and model code adjustments.

8.4.3. Further Activities Focusing on the <u>Methanol</u> Fuel Cell Vehicle

Assuming the successful and timely development of a cost-effective on-board methanol reformer, no other challenges to methanol fuel cell vehicles were found in this study to prevent their commercialization within the decade. There are, however, several issues to be addressed soon, ranging from fuel price and taxation practices to refueling infrastructure investment risks and toxicity concerns.

- On-board methanol **reformer technology must be proven as early as possible**, even if not economically feasible until actual market introduction or even later—unless the pilot demonstration vehicles use direct hydrogen-fueled FCVs, with the methanol reformer and fueling infrastructure then introduced commercially.
- Methanol's toxicity can be countered through expanded early development of denaturing agents, delivery system access safeguards, emergency response procedures, and continuing consumer education. **Planning of recommended practices for these solutions should begin** now in order to assure an acceptable level of safety against accidental ingestion or skin contact.
- **Flame invisibility requires resolution through early risk analysis and promulgation of appropriate standards.** This study's review finds methanol flame invisibility to be only a minor safety concern, due to the visible flame of other auto materials that would ignite in a fire. Otherwise flame visibility may need to be achieved through expanded research on additives that can avoid contamination of reformers or fuel cells.
- Methanol's low RVP carries the danger of a **flammable vapor space within the fuel tank, requiring early study and resolution.** It is well understood and not expected to be a major problem due to the availability of known solutions such as ignition-safe or external fuel pumps.
- **Methanol-over-gasoline spill** studies are needed now to settle this issue. Such spills could contribute to the spread of existing BTX plumes into groundwater, but may be a serious concern only in very large quantities of methanol sufficient to deplete oxygen in soil.
- **Direct methanol fuel cell research should continue.** DMFCs are promising in early demonstrations. They may be introduced soon for small-scale stationary uses, but still require significant development for vehicular use. In this study DMFCs are not assumed available for FCV market introduction unless that market entry is delayed for a decade or more. If successfully developed later, DMFCs will offer many benefits and help to assure longer-term use of methanol in FCVs.

8.4.4. Further Activities Focusing on the Gasoline Fuel Cell Vehicle

The commercialization strategy for gasoline-fueled FCVs may require the use of direct hydrogen or other fuel for the initial low-volume production vehicles, with a later transition to a gasoline-type fuel if and when the reformer technology is adequately developed. In addition, the earliest practical "gasoline" reformers may require a refinery fuel product other than conventional (CARB Phase III 2007) gasoline, because of the added challenge of avoiding sulfur contamination of the reformer.

- The initial "gasoline" used in FCVs could be a specially produced hydrocarbon with very low sulfur, such as the naphtha refinery stream—thus requiring a dedicated fuel delivery infrastructure similar to that for methanol or ethanol at least for the initial FCV introduction. **Studies of refinery product options and planning for their availability for market introduction must begin** as soon as fuel specifications can be derived from the reformer development efforts.
- With the use of a low-sulfur refinery product, whether a gasoline or naphtha, **the possibility of sulfur contamination through pipeline transport must be investigated soon.** If such contamination occurs, it could necessitate dedicated fuel transport and/or sulfur removal at the fueling station or on the vehicle, with potentially serious effects on infrastructure cost. Although this risk may prove to be insignificant, early study and resolution will be needed.
- A special refinery product may incidentally have a lower RVP, although not necessary for reformer operation, which could help qualify the fuel for improved PZEV emission status similar to the methanol FCV fuel option. **State regulatory personnel should assess this possibility in advance** and be ready to rule on it soon so that further R&D investments can be effectively directed.
- The lower RVP also carries the possibility of creating a **flammable vapor space within the fuel tank. This requires early study and resolution** but should not be a major problem due to the availability of known solutions such as ignition-safe or external fuel pumps.
- Attainment of the needed fuel characteristics at the refinery plus the possible need for separate tanks and fueling facilities at stations, will require **assurance of an adequate financial return and/or a risk-reduction mechanism** for investment risks and refinery operations disruption. This cost and risk may be somewhat less than those of other liquid fuels for FCVs, but should be included in the early fuel-financing and subsidy discussions.

8.4.5. Further Activities Focusing on the Ethanol Fuel Cell Vehicle

Ethanol may offer unique environmental and economic benefits in California as well as elsewhere due to the theoretical possibility of using local agricultural and forest waste as feedstocks, thereby dramatically reducing GHG emissions and creating employment within the state. Fuel security benefits are also exceptional due to ethanol's domestic feedstock sources and production. Substantial challenges exist, however. Ethanol's cost is too high for its use except in gasoline price emergencies, it has difficult reformer requirements similar to those of gasoline, and as with gasoline, the timely availability of an acceptable multi-fuel on-board reformer is uncertain. In addition, the future economics of ethanol production from cellulose are uncertain, and a complete new California infrastructure would be needed for ethanol feedstock supply, fuel production, delivery, and vending. This requirement in turn necessitates at least interim and possibly permanent ethanol supply from Midwest producers.

- Ethanol has the potential for unique indirect environmental benefits in the form of reduced air pollution and GHG (methane) release from forest and agricultural wastes, which will help to justify interim governmental financial assistance. Other feedstocks, such as municipal waste, also represent substantial societal benefits but are generally expected to remain uneconomical in the foreseeable future. **A more detailed accounting of these long-term options and their benefits and costs is needed to provide reliable estimates for further planning.**

- **Long-term nationwide ethanol supply limits and costs** will most likely be insurmountable challenges for the future broader FCV market using 100% ethanol, even if adequate quantities can be supplied to meet initial California needs. This conclusion leads to a dual-fuel strategy in which only a portion of the FCV demand will be met by ethanol. Although hydrogen is more efficiently produced by reforming 100% ethanol than gasoline, the same reformer can be used for both, including blends. They can be sold separately for different fueling stations or localities, or refiners could blend the two fuels within a range as needed to utilize the limited ethanol capacity most effectively and minimize the costs of all automotive uses (oxygenates, octane boosters, and FCV fuel). This multi-use approach can also help finance and speed the development of California ethanol production capacity. **This proposed strategy requires further early detailed study and outreach to judge its potential practicality and support.**

- **The flammable vapor space issue needs to be addressed soon.** This issue is comparable to the risk cited for methanol and low-RVP gasoline. It is not anticipated to be severe but must be resolved early.

- **Fuel quality requirements must be identified soon** through reformer development for sufficiently accurate assessment of the fuel production investment and price implications.

- **Ethanol purity** appears readily achievable but must be assured once fuel quality requirements are set. Possible contamination sources include both the production and transport systems. This issue is included here only because of the likely critical importance of FCV fuel purity, not because of any observed deficiency in the ethanol industry. It may or may not require investment in a higher level of quality control measures than now seen in the bulk fuel ethanol industry. **Needs, costs and potential difficulties with this level of quality control must be assessed soon.**
- The various **alternative ethanol source pathways need more study soon** in order to predict investment and fuel cost. These alternatives range from early or permanent out-of-state corn-based production to later use of in-state forest and agricultural wastes as well as municipal wastes.

Appendices

Introduction and Contents of Appendices

Introduction to Appendices

The appendices that follow are included to provide further details and perspective on some of the key issues presented in the body of the report. In some of the appendices, important details of methodology, assumptions, and data are given to support specific findings in the report. In other cases an appendix may document analyses done by team members that were not fully adopted in the final analysis but still contributed importantly to the study's methods and results. Still other appendices provide background information too detailed or anecdotal for inclusion in the main report but in the study team's judgment too valuable to exclude.

List of Appendices

Appendix

A Marketing the Uniqueness of FCVs

Robert Knight

Bevilacqua-Knight, Inc.

Introduction

Public market development for the first FCVs is much the same for all four fuel types. Some of the key marketing issues are covered in Chapter 3, such as the continuing roles for fleets, geographic limitations, customer types and vehicle models. This Appendix focuses on another key concern—how to maximize the early FCV's value to consumers. Will they see enough unique value to accept a premium price for these early FCVs? An initial premium price is often achievable with other new consumer goods, based on uniqueness and scarcity, and would help to cover the FCV's high initial production costs while volumes are necessarily low. And what can be done to increase that perceived value? Can other features be added to make the FCV both more readily acceptable, despite its innovation risk, as well as more uniquely valuable?

Will early FCVs offer unique value to consumers that will justify a premium price?

This is a critical issue for the FCV industry, including not only fuel cell and vehicle makers but also government regulators and fuel infrastructure providers. Initial FCV production costs will be high compared to conventional ICEVs and hybrids, and makers will naturally wish to price the FCVs to cover as much of those costs as possible. On the positive side, FCVs could have some valuable public policy-relevant attributes such as local pollution reduction, global climate management, reduction of foreign oil dependence and its implications for security and price, and overall resource conservation through efficiency of use and recycling. But in the eyes of the *consumer*, what will be uniquely valuable about the FCV that will encourage its choice as well as a possible premium price to help cover early-model costs?

The on-board demand for electric power will grow rapidly over the coming decade, due both to new technological opportunities and consumer desires. Renault recently projected the current average demand of 950 W to rise to 5 kW by 2006, and other sources have predicted power demands as high as 12 kW within the decade. For perspective, a typical home's peak power demand is about 5 kW, and an economical automobile engine operates at an output of under 10 kW most of the time although its capacity may be 75kW or higher. In this context an additional 5-12 kW electrical accessory load will be a major draw on the engine at times of high engine load such as acceleration.

The auto industry is moving toward a 42-volt electrical system to reduce I^2R resistive losses as one part of the solution. Some automakers are investigating the possible use of separate on-board auxiliary power units just for the electrical load. Hybrid vehicles will also be able to use—or enlarge—their motive-power batteries to help cover the added demand. However, all cases require additional power generation capability. The new power demands will include some functions that operate while the vehicle is in motion and others that operate while the vehicle is parked or stalled in traffic—requiring the engine or APU to be running and producing additional emissions.

Some possible future uses for automotive electric power are already emerging. Exhibit 3-2 provides a sampling of these and others being contemplated. They include mechanical functions of the vehicle itself, such as electric brakes, suspension, and steering, as well as accessory features for the consumer's discretionary use. Others will certainly be developed in addition to those listed. Note, however, that most could be offered in conventional vehicles as long as adequate electric power capacity is provided. This means that these features are not necessarily unique to FCVs. However, FCVs do offer the simplicity of utilizing the fuel cell's inherent excess power capacity instead of the complication of adding ICE engine power, batteries, and/or an auxiliary power unit.

If these electrically powered functions are to be made available in all vehicles, what is uniquely valuable about the FCV?

There are several characteristics unique to FCVs that may become increasingly valuable to consumers during this decade:

- **Stationary power:** In the eyes of consumers, this will be the defining difference of FCVs. Many future conventional vehicles will be able to generate electrical power while either moving or parked. However, some types of FCVs will be able to operate at high electrical output for long periods, unattended and indoors, with no harmful emissions. This will open a vista of new vehicle functions such as home emergency power, recreational power sources, discretionary distributed generation, and even mobile offices at the beach or coffeehouse while waiting for the rush hour traffic to subside. To enhance these and other uses, new vehicle configurations could evolve later to provide space flexibility and conveniences never before imagined.
- **Less fuel price sensitivity:** A marketing advantage of fuel cell vehicles will be their fuel economy: they will go farther than combustion-engine vehicles or even hybrids on a given amount of energy (c.f., Argonne, 2001). Even though the demand for fuel now appears to be remarkably insensitive to price at present, it may become a major factor in vehicle selection--particularly if a global oil price crisis emerges during the decade. This could prove to be true even for many luxury car buyers if gasoline prices move into the \$5-\$10/gallon range. However, FCV fuel economy will be a market advantage only if the fuels they use are priced so that there is a true operating

Exhibit A-1: Examples of Increased Future Vehicle Electric Power Demands

More computer power for rapidly increasing control and status-report functions throughout vehicle	Extensive on-board communications, e.g., internet, fax, phone, interactive GPS services	Complete mobile office: more powerful/capable computers, printers, fax, e-mail, etc.
Computer-controlled, power-assisted active suspension	TV, video, phone and internet access to all seats	Therapeutics, e.g., massage seats, heating pads, etc.
Electrically actuated brakes and power-to-wheel distribution	Voice-actuated controls and status reports	Electronic active windows for light and heat control
Electric “drive-by-wire” steering	Task-based cabin lighting	Refrigerator/freezer, beverage cooler, etc.
Video rear-view "mirrors"	Outdoor working lights and controls	Microwave food warmer
Collision-avoidance radar (and eventual autopilot functions)	Active tire inflation adjustment and status monitoring for lockup	Cabin preconditioning (including temperature maint. when parked)
Electrically actuated doors with safety locking assurance	Extensive automatic crash safety restraints and protections	Driver alertness monitoring and intervention
Electric a/c compressors for engine-off use	Multi-audio with higher-power speaker systems	Electrically assisted cabin reconfiguration for stationary uses
Night vision lighting enhancement	Exterior AC power supply	Loading lifts and ramps
Video alarms	High-rpm engine start and hybrid control	Magnetic suspension dampers

cost advantage rather than merely making them competitive or equal on a cents/mile basis. This will be a substantial challenge and may not be possible due to FCV fuel production and delivery costs in the early years; however, an operating cost advantage should be viewed as a possibility when considering fuel price subsidies for FCVs.

- **Environmental self-image:** Many industry observers believe that vehicle users talk environmentalism but want neither to pay more for it nor sacrifice other customary features for it. However, consumer concern may well increase in coming years over global warming, foreign oil supply disruptions, and high-consumption lifestyles. Recent consumer surveys indicate that environmentalism may be moving into the category of “core values” with enduring and growing interest rather than just another fluctuating issue of the day. If so, a growing number of consumers may wish to align themselves with choices--such as FCVs--that allow them to act in support of environmental concerns. Such interest may be intensified still more through marketing that gives it high social status. This may create a significant new willingness to pay a voluntary premium to have an early FCV, and should be included as a factor in FCV market research.

These unique features, particularly the ready availability of electric power, could cause a revolutionary change in the public's perception and use of vehicles. For the first time, the passenger car could be something much more than a conveyance, becoming a radically different source of power for many functions. The existence of FCVs could even lead to the creation or transformation of some of these new functions—with results as unpredictable as using a telephone in a car would have been only a few years ago.

But would these features be valued enough in the first few years of FCV availability to justify a premium price? Achieving such new value would require the development of a much more extensive infrastructure for vehicle power connections, metering, payment, and additional fueling sources and methods. This would develop only slowly. During the first few years, such premium FCV value will be viewed as a potential monetary benefit rather than an actual one--an important sales feature but not a justification for premium FCV prices until those valuable new functions actually exist. An early "showcase" deployment of such features will demonstrate their value and increase demand, paving the way for acceptance of a premium price as the required extra infrastructure matures.

What characteristics of the initial mass-market FCV "product package" will be needed to assure adequate consumer acceptance?

It is crucial that the initial FCVs be accepted with enthusiasm in order to build the market momentum needed to overcome early market-coverage limitations, recover the huge initial investments, and move toward realization of the FCV's societal advantages. This is particularly important for FCVs, due to natural consumer concerns over the uncertainties of a radical new technology in so large an investment as a new vehicle. This may require a comprehensive "product packaging" strategy that adds a portfolio of extra features to position the FCV as a special value and reduce its perceived risks when compared to conventional vehicles. This concept is drawn from the battery electric vehicle experience, in which EVs were widely judged almost exclusively negatively due to concerns over limited range, because the total product packaging failed to demonstrate more compelling positive features.

Examples of FCV package elements that could contribute to such a “product packaging strategy” include the following:

- Price subsidies for both vehicle and fuel in the first several years as volume grows, to assure pricing that the consumer perceives as a benefit rather than a deterrent
- Extensive public education, media support, and visible demonstrations to build confidence in FCV safety, practicality, and status (e.g., via feature film placements)
- Clear demonstration that the FCV meets or exceeds consumer expectations for conventional autos in the basic automotive characteristics of economy, performance, range, appearance, appointments, and conveniences/luxuries
- Extraordinary warranty and repair protection, including premium roadside service and quick free unlimited repairs or replacements, to reduce perceived risk of reliability problems and costs and to show added value
- High-quality insurance coverage at competitive or better cost than available for conventional vehicles; possibly included in vehicle purchase or lease price
- Guaranteed buyback or competitive lease terms, to eliminate concerns over low used-car value due to early obsolescence of initial models
- Use of visually dramatic, easy-to-use, fueling equipment designs to emphasize the futuristic quality of FCVs and counteract possible perceptions of inconvenience and difficulty
- Use of GPS/GIS, or global positioning and information transfer systems (already expected to be common in new vehicles by mid-decade), to facilitate location of the less-common FCV fueling stations and further counter perceptions of possible inconvenience; possibly free for first year or two
- Early rollout of a variety of FCV models, to appeal to a broader range of market segments; could be built on same platform and production line

This range of packaging elements differs dramatically from prior efforts on behalf of other recent alternative-fuel vehicles using batteries, natural gas, or alcohol fuel blends. This degree of comprehensiveness as well as intensity is unprecedented. Not all these elements may be necessary; detailed market research will be required to identify the most valuable package of features.

Appendix

B Fuel Economy Comparisons for FCVs

Stefan Unnasch[14]

Arthur D. Little, Inc.

Introduction

Fuel-cycle emissions, including CO_2, correspond largely to the total volume of fuel produced. As such, fuel consumption is a strong driver in determining total fuel-cycle emissions. In general, as more fuel is produced, more feedstocks are extracted and transported, production facilities operate with greater throughput, and trucks and pipelines move more fuel to fueling stations. This section reviews the data inputs used in this study, methods for estimating fuel economy, and the sets of fuel economy assumptions that were used for the fuel-cycle analysis. The information in this study is based on data and model estimates that were analyzed as part of a study performed by the California Energy Commission. (Unnasch, S., Browning, L., "Fuel Cycle Energy Conversion Efficiency, Status Report," Prepared for California Energy Commission and California Air Resources Board, May 2000.)

Fuel Economy Data and Projections

Fuel economy estimates for FCV technologies were derived from comparisons of existing vehicles and model estimates. These comparisons were made for vehicles that are close to identical except for fuel. A consistent set of fuel economy estimates was determined by investigating the ratio of energy economy (mi/Btu) for alternative vehicles to comparable gasoline vehicles. These energy economy ratios (EERs) were then applied to a single baseline gasoline fuel economy.

Vehicle comparisons ideally represent vehicles in similar classes and performance capabilities. This is not necessarily straightforward, as various vehicles have different attributes that are particular to the technology and are not replicated in another vehicle technology. This issue will be discussed further in the following subsections.

---

[14] The author acknowledges the substantial contributions of Dr. Sandy Thomas to this derivation of fuel economy estimates.

Baseline Gasoline Vehicles

Gasoline vehicle fuel economy is estimated in order to provide a basis for determining a consistent set of assumptions for the fuels considered in this study. Baseline fuel economy was determined for one vehicle class, namely subcompacts. Subcompacts represent one of the most fuel-efficient classes of vehicles and many of the advanced technology vehicles are in this class.

Average fuel economy was determined for sixty-eight model year 2000 gasoline vehicles within this class (high performance vehicles were eliminated from the data). The US EPA reports fuel economy for all certified vehicles. Using undiscounted fuel economies[15] the average fuel economy for the 68 vehicles was 32.2 miles per gallon. To account for real world conditions, this certification fuel economy should be discounted by about 15 percent resulting in an on-road fuel economy of 27.4 mpg[16]. Assuming a 10% improvement in fuel economy by the time the 40,000 v/yr milestone is reached, the average subcompact on-road fuel economy is 30.16 mpg.

Subcompact Vehicle Fuel Economy

Fuel	*LHV Btu/gal*	*FE mpg*	*Discounted mpg*
Gasoline (Indolene)	114,244	32.26	27.42
California Phase 2 RFG	113,000	31.91	27.12
California Phase 3 RFG	113,500	32.05	27.24
By 40,000 v/yr milestone: Estimate increase by 10%			30.16

Fuel Cell Vehicles

Fuel Economy data for prototype hydrogen fuel cell vehicles built by Ford and Daimler-Chrysler have been reported. Comparisons can be made with similar gasoline-fueled vehicles. Steam reformed methanol vehicles and autothermal reformer gasoline fuel cells are being tested in the laboratory. Several academic institutions have developed computer models of fuel cell vehicles to predict fuel economy for these technologies. Using this limited modeling and vehicle data EERs for a variety of vehicle technologies were estimated as part of the California Energy Commission study. This study included

---

[15] The US EPA Fuel Economy Guide lists discounted fuel economy results to account for real world driving. Undiscounted values are published at US EPA's Fuel Economy website (www.fueleconomy.gov). Undiscounted values provide a better comparison among various alternative technologies and fuels.

[16] US EPA's adjustment for on-road driving is City FE x 0.9 and Highway FE x 0.82.

review of fuel economy estimates with a technical advisory committee (TAC) that included carmakers, electric utilities, and state agencies. The EERs represent a consensus value that takes into account carmaker experience and projections for future gasoline and fuel cell vehicles.

EERs of 1.50 to 1.74 were estimated for hydrogen fuel cell vehicles, 1.39 to 1.54 for methanol steam reformed fuel cell vehicles, and 0.97 to 1.35 for gasoline reformed fuel cell vehicles. These estimates are highly speculative and will need to be refined as these technologies become more commercial. The TAC provided significant input on the fuel economy of fuel cell vehicles. Carmaker comments indicated that EERs above 2.0 for future hydrogen fuel cell vehicles did not reflect identical gasoline and hydrogen vehicles. Data for hydrogen vehicles and modeling estimates are shown below.

Ford Fuel Cell Vehicle (P2000)

	Gasoline Equivalent Fuel Efficiency			
	Urban	*Highway*	*Combined*	
Hydrogen FC vehicle	4.22	2.92	3.51	l/100 km
			67.11	mpeg
Comparable Gasoline Vehicle (5-passenger P2000)			44.20	mpg
Resulting Energy Efficiency Ratio			1.52	

Daimler-Chrysler Hydrogen Fuel Cell Vehicles (A-Class)

	H_2 FE	*Gasoline Equivalent FE*	
NECAR IV	1.1 kg H_2	4.4	l/100 km
		53.46	mpeg
Gasoline equivalent vehicle (A-Class)		7.1	l/100 km
		33.13	mpg
Resulting Energy Efficiency Ratio		1.61	

Summary of Fuel Cell Vehicle Modeling Studies

A. Methanol FCVs

Vehicle	*FC Fuel*	*Fuel Cell mpeg*	*Gasoline mpeg*	*EER*	*Wt. Ratio*	*kJ/kg*	*Btu/mi*	*mpeg*
CARB Reformer Report	M100, FUDS	46.3	24.6	1.88	1.14			
Volvo	M100, ECE	41.1	25	1.65	--	1800	2747	41.1
Princeton	M100	61.7	35	1.76	1.57	1200	1831	61.7
Princeton	M100	29.7	27.5	1.08	1.71	2490	3800	29.7
IKA Model	M100, FUDS			1.39				
IKA Model	M100, FUDS			1.54				
DTI NREL Report	M100 FUDS	44	30	1.47				
GM-Silverado	Methanol	~30	20	~1.5				
GM-Silverado	MeOH FC hybrid	~31	20	~1.55				
FZ Juelich	M100 ECE	74.1	47.4	1.56	--			

B. Gasoline FCVs

Vehicle	*FC Fuel*	*Fuel Cell mpeg*	*Gasoline mpeg*	*EER*	*Wt. Ratio*	*kJ/kg*	*Btu/mi*	*mpeg*
DTI NREL Report	Gasoline, FUDS	29	30	0.97				
Princeton	Gasoline, FUDS	65	35	1.86	1.47	1140	1740	65.0
Princeton	Gasoline, FUDS	37	27.5	1.35	1.76	2000	3052	37.0
Kreutz	Gasoline, FUDS	40.9	33.4	1.22	1.28			
GM—Silverado	Gasoline FC	~27	20	~1.35				
GM—Silverado	Gasoline FC Hybrid	~30	20	~1.5				
GM—Silverado	Gasoline Hybrid	~24	20	~1.2				

C. Ethanol FCVs

Vehicle	*FC Fuel*	*Fuel Cell mpeg*	*Gasoline mpeg*	*EER*	*Wt. Ratio*	*kJ/kg*	*Btu/mi*	*mpeg*
GM-Silverado	Ethanol FC	~28	20	~1.4				
GM-Silverado	Ethanol FC hybrid	~32	20	~1.6				
GM-Silverado	E85 hybrid	~24	20	~1.2				

D. Hydrogen FCVs

Vehicle	*FC Fuel*	*Fuel Cell mpeg*	*Gasoline mpeg*	*EER*	*Wt. Ratio*	*kJ/kg*	*Btu/mi*	*mpeg*
DTI NREL Report	Hydrogen, FUDS			2.60				
DTI NREL Report	H_2 FUDSx1.25	65	30	2.17				
IKA Model	Hydrogen, FUDS			1.63				
IKA Model	Hydrogen, FUDS			1.74				
GM Silverado	Hydrogen FC	~43	20	~2.15				
GM Silverado	Hydrogen FC hyb	~48	20	~2.4				

All GM values were taken from graphs and are approximate

High Efficiency Vehicles

Vehicles such as the VW diesel Lupo (Birch); Honda Insight gasoline hybrid electric and the GM EV1 can be categorized as high efficiency designs. Weight reductions and low drag coefficients result in fuel economy improvements that apply to both gasoline and alternative vehicle drive trains. A category of high efficiency vehicles was also analyzed. This class is similar to the concept for the Partnership for New Generation of Vehicles (PNGV). Baseline lightweight gasoline cars were estimated to be 50 percent more efficient than typical subcompacts, resulting in a baseline gasoline fuel economy of 45.2 mpg. This value is consistent with PNGV assessments of fuel economy.

US DOE projected estimates for several different vehicle types, sizes and timeframes. This data is particularly useful as it closely matches the methodology used in this study. The ratio shown below is the estimated improvement in fuel economy of each of these technologies as compared to a gasoline baseline. The US DOE information is generic for fuel cell vehicles reflecting a mix of methanol and hydrogen vehicles. This study uses estimates for methanol vehicles with steam reformers that will be less efficient than hydrogen fueled vehicles.

Projected Ratio of Improvement in Fuel Economy (EER)[a] by Vehicle Type and Technology

Technology	*Small Car*	*Large Car*	*Minivan*	*Sport Utility Vehicle*	*Pickup and Large Van*
Electric	4	N/A[b]	4	4	N/A
Advanced Diesel	1.35	1.35	1.45	1.45	1.35
Fuel Cell	N/A	2.1	2.1	2.1	N/A

[a]EER = energy economy ratio
[b]N/A = not analyzed unlikely vehicle market
Source: US DOE

US DOE's fuel economy estimates were used in a vehicle choice analysis that includes a number of factors, including vehicle availability, size, purchase cost, fuel price, fuel economy, range, expected maintenance costs, truck space, acceleration, and top speed in conjunction with a vehicle choice analysis. The vehicle choice analysis simulates the preference of buyers to purchase vehicles that maximize their utility and uses current market research data to inform what these choices are. In this way, the model provides output that shows the expected penetration of each vehicle type over time.

Fuel economy estimates used in the economic analysis are shown below. The low and high ranges are presented in the discussion of greenhouse gas emissions.

Technology	*FCV value for fueling station cost analysis*	*Low*	*High*
Hydrogen PEM FC	1.9	1.61	2.0
M100 SR/PEM FC	1.52	1.39	1.55
Ethanol ATR/PEM FC	1.4	1.25	1.4
Gasoline ATR/PEM FC	1.39	1.25	1.4

Appendix
C Local Emissions and Greenhouse Gas

Stefan Unnasch

Arthur D. Little, Inc.

Background

This Appendix provides an assessment of the air emission impacts of operating fuel-cell powered vehicles (FCVs). Included in the assessment is information on four fuels that could power FCVs – hydrogen, methanol, hydrocarbon fuel similar to gasoline, and ethanol.

The emission impacts that were analyzed include local air emissions and greenhouse gases. Impacts from the production, distribution, and end use of fuel were considered. In addition, comparisons of environmental impacts of manufacturing vehicles and fuel production facilities were reviewed.

Local emissions include hydrocarbons, NO_X, CO, particulate, and toxics. These pollutants occur both in urban areas as well as throughout the fuel production chain. The greenhouse gases, CO_2, methane, and N_2O are of a global concern. The location of these emissions is immaterial since their impact is the long-term potential for global warming.

These environmental impacts are important to a variety of stakeholders. California Air Resources Board (CARB) vehicle emission standards include vehicle exhaust and evaporative emissions. Fuel cycle emissions represent a significant fraction of emissions associated with vehicle operation.

Due to the significant contribution of fuel cycle emissions to total pollution, the CARB regulations give credit to vehicles with low fuel cycle emissions. The low fuel cycle allowance is one element of the partial zero emission vehicle (PZEV) allowance program, which provides partial allowances for vehicles that have some zero emission characteristics. Vehicles that emit less than 0.01 g/mi of NMOG qualify for a 0.2 PZEV allowance.

Greenhouse gas emissions (GHGs) are also an important part of the environmental discussion in California and throughout the world. While CARB does not have the authority to regulate greenhouse gas emissions, it does consider the effect of its emission rules on greenhouse gas emissions.

Available information

A variety of studies consider the environmental impacts of various fuel options. Many studies examine greenhouse gas emissions and total emissions from fuel production. Fewer studies examine local emissions that would be attributed to fuel production and distribution specific to California.

Table 1 shows studies that examine the environmental impacts of fuels. A.D. Little has been working with the CEC and CARB to revise fuel cycle emission analyses for fuels used in California. The results of these fuel cycle studies are generally applicable to fuel cell powered vehicles when the results are represented on a g/gallon of fuel basis (or g/lb of hydrogen). These results can also be presented on a g/MMBtu basis. The results are presented per gallon as this eliminates potential confusion between higher and lower heating values and translates directly to a vehicle's fuel consumption.

Argonne National Laboratory (ANL) has also performed an extensive review of greenhouse gas emissions from different fuel options. Other notable studies are identified in Table 1. These studies all determine CO_2 and other greenhouse gas emissions on a g/mile basis. With some effort, the results of these studies were manipulated to show the values in grams per gallon. It appears that most of the discrepancies between different greenhouse gas studies rests with the vehicle fuel economy assumptions. GM recently released a study on GHG emissions and energy consumption from fuel cell powered vehicles. This study was done in cooperation with ANL and incorporates an updated analysis of the GREET model.

Table 1. Greenhouse Gas and Fuel Cycle Emission Studies

	M	*D*	*LPG*	*G*	*E*	*H*	*LNG*	*CNG*	*FTD*	*Elec*
ADL 2000, CARB	✓	✓	✓						✓	✓
ADL 2000, CEC	✓		✓	✓	✓	✓		✓		✓
ANL GREET 1.5a	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
GM/ANL	✓	✓		✓	✓	✓		✓		✓
Pembina, 2000	✓			✓		✓				
(S&T)2	✓			✓		✓				
Dept. of Agriculture					✓					
NREL, 1999	✓			✓	✓					
Acurex 1996	✓	✓	✓	✓	✓	✓		✓		✓
DTI	✓			✓		✓				✓

Methanol (M), Diesel (D), Liquified Petroleum Gas (LPG), Gasoline (G), Ethanol (E), Hydrogen (H), Liquified Natural Gas (LNG), Compressed Natural Gas (CNG), Fischer-Tropsch Diesel (FTD), Electric (ELEC) for EV or electrolysis.

The studies listed in Table 1 all identify well to wheel emissions. Another aspect of the fuel cycle that is generally considered to be less relevant is the energy inputs and related emissions for fuel production facilities, infrastructure, vehicle manufacturing, and recycling. These emission impacts are roughly 10 to 20 percent of the total vehicle impact and do not differ considerably among the fuel options. The relevance of these facility impacts is unclear as the lifetime and specific details of fuel production facilities as well as other economic factors affects how these emissions might be viewed by policy makers.

Another significant impact is the economic and environmental consequences of platinum production. While platinum for fuel cell powered vehicles can be recycled, under some scenarios, platinum demand will increase significantly. The environmental impacts largely affect the local region where platinum is mined and processed. Platinum recycling from fuel cells should be relatively straightforward as the platinum is imbedded in the fuel cell membrane. Recycling platinum from catalytic converters is more complex as the platinum is imbedded on an alumina catalyst.

Fuel Economy

Fuel economy assumptions significantly impact the conclusions of environmental assessment studies when the emissions results are reported in grams per mile, a common metric. With multiple fuel economy values for alternative fuels and baselines in each study, the conversion from grams per gallon or pound of fuel to grams per mile generates a range of results that are not directly comparable. Without comparable emission ranges, it is not possible to make any preliminary conclusions about the benefits of different types of vehicles. Fuel economy values are not presented here. Therefore, the g/gallon or g/lb values alone do not provide a basis for evaluating the environmental impact of FCVs.

Local Emissions

Local emissions that receive the most attention for FCVs include NO_X and hydrocarbons as these are smog precursors. Non-methane organic gases or NMOG emissions are of concern because these occur throughout the fuel distribution chain as well as from vehicle fueling, startup, and fuel system evaporation.

Emissions from fuel cell vehicles include vehicle exhaust and evaporative, refueling, and related fuel cycle emissions. Fuel cell powered vehicles are considered candidates for meeting the lowest emission levels. This suggests that gasoline, methanol, and ethanol vehicles may all prove able to comply with the SULEV or PZEV standard. As fuel cell reformers have intrinsically low NO_X emissions, fuel cell powered vehicles may have an advantage in NO_X emissions compared to other vehicle options.

Fuel cell vehicles with reformers might offer some emissions advantages during steady-state operation, but these emissions benefits have not been quantified. The principal smog precursor emissions advantage from fuel cell powered vehicles would be a reduction in refueling emissions due to increased fuel economy. The lower fuel vapor pressures of ethanol and methanol would also help to reduce emissions.

Table 2 identifies available information on fuel cell vehicle exhaust emissions. Refueling emission results are available from fuel cycle studies. At this time, data on fuel cell vehicles is limited and the best estimate is that they will meet SULEV standards and achieve zero NO_X emissions. Vehicle tests are limited and challenged by a lack of cold start performance as well as detection limit issues with exhaust measurements.

Table 2. Summary of Vehicle Emission Data and Predictions

Source	*Topics*	*Vehicles*
Acurex 1999, Reformer Emissions	Exhaust emissions modeling	Gasoline, methanol, ethanol, LPG ATR, Methanol SR
FZJ Modeling Studies	Exhaust emissions modeling	Methanol SR
Necar 3 in Acurex, 1999	Exhaust emissions data	Methanol SR
Zafira in Acurex, 1999	Exhaust emissions data	Methanol SR
DTI, 1999	Exhaust emissions modeling	Gasoline ATR, methanol SR
UC Davis 1998	Exhaust emissions modeling	Gasoline ATR, methanol SR
Ogden 1998	Exhaust emissions modeling	Gasoline ATR, methanol SR

The principal non-vehicle emissions that are affected by fuel cell powered vehicles are refueling emissions. While significant emissions occur from oil refineries, oil production, and methanol production, use of the marginal gallon of gasoline or methanol does not result in a significant increase in these types of emissions in California. Similarly, most ethanol plants may be sited with existing biomass power plants. These facilities may also have limits on emissions. Furthermore, ethanol production in California will clearly result in a reduction in emissions associated with biomass feedstocks.

CARB's analyses of gasoline and electric vehicle emissions include only marginal fuel cycle emissions rather than the average emissions from fuel production facilities. Using marginal emissions as a basis for assessing fuel production emissions has evolved over the past 5 years of vehicle emission policy discussions in California. Fuel production stakeholders find the marginal emissions to reflect their efforts to reduce emissions from fuel production facilities and to comply with caps on such facilities. Others have considered the marginal emission metric to not consider all potential environmental consequences. As more fuel is produced from refineries operating near capacity and more fuel is hauled through pipelines and by tanker ship, the potential for accidental releases could increase. These environmental risks indicate that other effects might be considered in the assessment of vehicle emissions.

Taking into account the marginal emission considerations described above, the most significant air quality impact from fuel cell powered vehicles is a reduction in refueling emissions. Refueling emissions have been studied in several fuel cycle studies. Unfortunately, such studies do not incorporate the latest emission reductions that would be applicable for refueling stations in California. These emissions are largely affected by stage 2 vapor recovery and on-board refueling vapor recovery (ORVR). The refueling emission reductions have been assessed for methanol fuel in a recent study for the CARB. Parallel estimates for methanol, ethanol, and conventional gasoline are presented here.

Table 3. Summary of NMOG Emissions Including Refueling

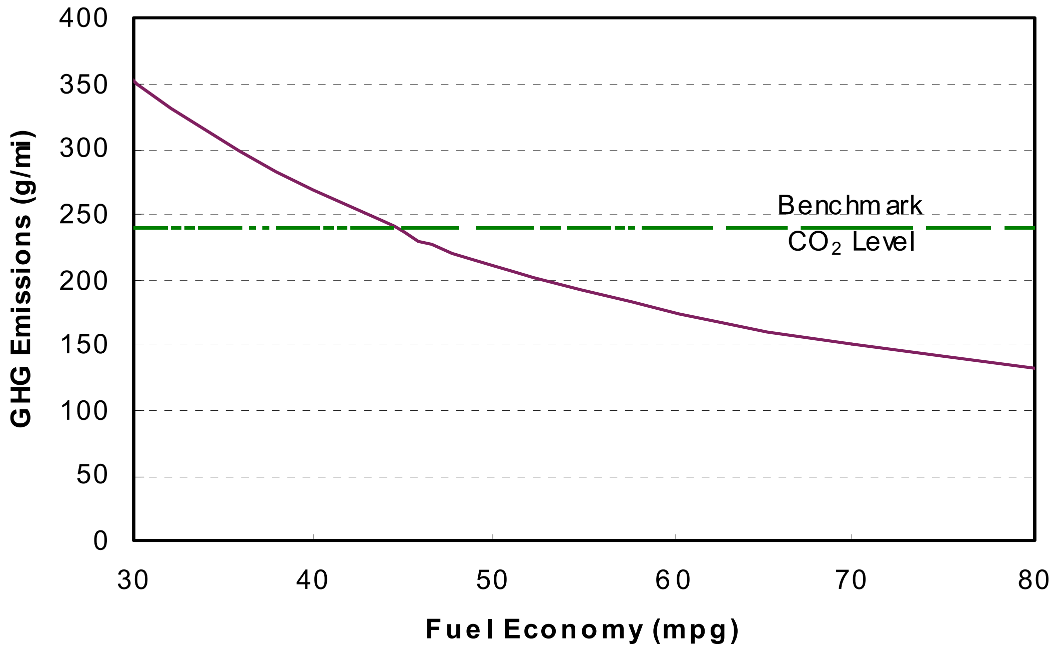
	NMOG
Gasoline	~1 g/gal
Low RVP Naphtha	~0.4 g/gal
Methanol	0.4 g/gal
Ethanol	~0.4 g/gal
Hydrogen, local reformer	< 0.2 g/lb

Global Climate Change Emissions

Greenhouse gas emissions from various fuels are important in determining which fuels have the least potential impact on climate change or the greatest value for carbon credits. Several studies report greenhouse gas emissions for gasoline, methanol, hydrogen, and ethanol. The ranges of greenhouse gas emissions are found in the literature for baseline gasoline, hybrid electric gasoline, and several fuel cells. These values include both vehicle-related CO_2 emissions, if relevant, and emissions associated with the production of each fuel. All values used are standardized for similar vehicle characteristics.

Figure 1 illustrates how the GHG factors in Table 4 relate to emissions on a per mile basis when vehicle fuel economy is taken into account (g/mi emissions = g/gallon ÷ mpg). GHG emissions are reduced as fuel economy (in mpg) increases. This method of presentation was selected since assessing the fuel economy of FCVs was not intended to be a focal point of this study.

Figure 1. Greenhouse Gas Emissions for Baseline Gasoline Vehicles and Benchmark CO_2 Level



Also shown in Figure 1 is a GHG benchmark value based on the European tailpipe CO_2 standard. This value reflects the 120 g/km tailpipe standard. If a gasoline vehicle emits 120 g/km, total fuel cycle CO_2 emissions would be about 148 g/km (8500 g/gallon from the vehicle and 2000 g/gallon from fuel production). Therefore 240 g/mi was taken as a benchmark level of CO_2 emissions that could be applied to all fuels as it takes into account both vehicle operation and fuel production.

Table 4 shows the values used for greenhouse gas emissions. These are weighted values for CO_2, CH_4, and N_2O. The latter two pollutants have greenhouse gas potentials that are 21 and 310 times greater than CO_2, respectively. The Intergovernmental Panel on Climate Change developed these weighting factors to more appropriately determine the global warming potential due to different types of emissions. Although CO_2 is a less potent chemical than CH_4 and N_2O, it is still the focus for global warming potential since it is produced during combustion at a much greater rate than the other pollutants. Carbon monoxide, hydrocarbons, and NO_X have minor greenhouse gas effects but they are not included in the greenhouse gas factor.

Table 4. Range of Greenhouse Gas Emissions for Various Technologies and Fuels

Fuel Option	*GHG Factor Range*	*Units*
Gasoline Baseline	10,800-11,500	g/gal
Naphtha, Zero Sulfur HC	10,200-10,800	g/gal
Methanol	5,450-6,000	g/gal
Ethanol	1,500-5,000	g/gal
Hydrogen, electrolysis	7,100-10,000	g/lb
Hydrogen, local NG	5,600-6,500	g/lb

The greenhouse gas factor range depends on assumptions about the efficiency of processes for making fuel, electricity, and characteristics of the vehicles themselves. Since gasoline in a conventional vehicle is well understood, this range seen in Table 4 is small. However, for other fuels, the range of greenhouse gas factors is large because of the wide range of production technologies that can be used to produce various fuels.

Table 5 illustrates the assumptions that affect GHG emissions for various fuels. The most significant variables are the efficiency of methanol and hydrogen production. Some arguments have been made that future methanol and hydrogen production will be more efficient in order to make the best use of feedstocks; however, tradeoffs between capital and operating costs (and possible GHG reduction credits) will impact the efficiency of fuel production.

Another important factor that affects GHG emissions is the energy input for hydrogen compression. The estimates of compressor energy are largely based on thermodynamic calculations rather than power meter readings on compressors.

The energy inputs for hydrogen from electrolysis provides the widest range of uncertainties. The source of the power generation as well as the efficiency of power generation affects the GHG emissions. In California, hydro and nuclear power are considered as base loads so marginal power for FCV hydrogen production would not be produced from these resources even if they contribute to the generation mix. Furthermore, future growth in these resources is not anticipated. Most marginal generation in California is derived from natural gas power plants. The marginal efficiency of the generation system depends on the time of day and the amount of available generation capacity (reserve margin). The efficiency of the generation system is being considered in a study for CARB and CEC.

Table 5. Key Assumptions Affecting GHG Emissions

Fuel Option, Assumption	*Range*	*Comments*
Hydrogen ATR efficiency and gas cleanup	50 to 65 % (HHV)	Existing technology
Hydrogen SMR efficiency	65 to 75% (HHV)	Assume 72%
Methanol production efficiency	65 to 72% (HHV)	Assume 71%
Hydrogen compression	0.7 to 1 kWh/lb	Assume 0.8
Hydrogen, electrolysis from renewables	Assume contractual mechanism that enables new wind power to be produced with FCV demand	
Hydrogen, electrolysis from NG	39 to 55% power generation (HHV)	Assume 48% based on night time supply

Renewable as well as low GHG pathways are possible for all of the fuel options. The most prominently discussed options include the following:

- Ethanol from corn with starch fermentation
- Ethanol from woody biomass with acid or enzyme processing and fermentation
- Methanol from landfill gas with small scale reformer
- Methanol from biomass gasification
- Methanol from sequestered CO_2 with renewable hydrogen
- Hydrogen from landfill gas with small scale reformer
- Hydrogen from biomass gasification
- Hydrogen from electrolysis with renewable power

Appendix

D Fueling System Capital Cost Estimates[17]

Sandy Thomas

Directed Technologies, Inc.

Hydrogen Station Costs

Hydrogen fueling is the most complicated alternative since there are many major options (trucked-in liquid hydrogen, trucked-in compressed hydrogen in tube trailers, electrolyzers and natural gas or liquid fuel on-site fuel reformers). Furthermore, several of these major options have variations in terms of fueling capacity or type of fuel processor. For purposes of bounding the total investment costs required, this study uses the following choices for each of three time intervals:

Prior to the pilot phase, assume that 15 fueling stations (in addition to the West Sacramento facility, AC transit in Alameda, and any other hydrogen bus refueling systems) are added – five each liquid hydrogen, tube-trailer hydrogen and electrolyzers. The costs for these installations in small quantities were estimated in a previous activity sheets and are summarized in the table below.

During the pilot phase, which can be several years, assume that 100 more fueling stations are installed in preparation for market introduction, including 10 liquid hydrogen systems, 10 more electrolyzers and 80 natural gas reformers. The natural gas reformers are favored over the electrolyzers due to lower projected fuel costs and, more importantly, substantially lower greenhouse gas emissions. In addition, some of these natural gas reformer systems could be replaced with on-site liquid fuel reformers. No significant capital cost savings would be expected with the liquid fuel reformers, since the reformer is a small part of the total fueling system, so the net investment costs should be similar with natural gas or methanol fueling appliances.

For the first several years of actual FCV market introduction (until at least the 40,000 vehicles/year milestone), this study assumes that factory production of natural gas-based integrated fueling appliances begins. The appliances would be installed at local gasoline stations, with compressed hydrogen storage tanks located at the edge of the property.

---

[17] This analysis was a principal reference in the study team's broader development of infrastructure cost estimates, particularly for hydrogen stations. Although the team made some upward adjustments to this paper's estimates, based on other sources such as the EA Engineering study on methanol station costs and imputs from CaFCP members, its logic and basic data were the basis for the cost estimates presented in Appendix C (Unnasch).

Fueling appliances would be produced in three sizes, adequate to support160, 400 and 800 fuel cell vehicles. These appliances would refuel approximately 20, 50 and 100 FCVs each day. As a frame of reference, an average gasoline station fuels 175 cars per day, a convenience store about 78 per day and a large pumper station almost 300 per day. In a mature FCV market, then, a larger hydrogen-fueling appliance would be required.

In this study it is assumed that these appliances would be transportable, such that stations could start with smaller fueling systems and then either add capacity or replace a small fueling appliance with a larger unit. The smaller unit might then be transferred to a new fueling station with fewer FCV customers. In this way the fueling infrastructure can be kept manageable, avoiding some of the "chicken and egg" infrastructure/FCV dilemma.

The total hydrogen infrastructure investment costs for the three time periods are summarized in Table 1. With this study's cost scenario, some $340 million would be required to install 1,100 hydrogen-fueling appliances, or an average of $304,000 per station.[18] The natural gas reformer systems would have to be larger for a mature FCV market, but we would not expect significant cost increases per station, since the costs would decrease with increased production volume.

For example, this analysis projects that a natural gas reformer system to support 2,000 FCVs (250 cars/day) would cost $460,000 in production quantities of 1,000 or more. The hydrogen produced at such a station would cost about $1.79/kg with natural gas at $6/MBTU (HHV), electricity at 6 cents/kWh and a 10% real, after-tax return on investment. This would correspond to gasoline selling at 82 cents/gallon, assuming a FCV with 2.2 times higher fuel economy than the conventional gasoline ICE vehicle. Hence hydrogen from such a station could compete with untaxed wholesale gasoline at these cost levels.

Table 1. Estimated Investment Cost for Hydrogen Fueling Systems

	Capacity (FCVs/day)	*No. of Stations*	*Unit Cost (US$1,000)*	*Installation ($US1,000)*	*Total Cost ($US1,000)*
A. Prior to pilot phase					
Liquid H_2 Vaporizer	Up to 85	5	485	50	2,675
Tube Trailer	Up to 11	5	330	15	1,725
Electrolyzer	4	5	250	25	1,375
Total for Period		15			5,775
B. Early Market Introduction (i.e., first ~4-5 years)					

[18] Both the assumed number of stations and their estimated costs (for all fuels) as cited in this background paper were revised by the Study Team for the main report.

Liquid H_2 Vaporizer	Up to 85	10	300	40	3,400
Electrolyzer	30	10	325	20	3,450
NG Reformer	20	80	200	50	20,000
Total for Period		100			26,850

C. Beginning of Mass Production (assume 2 year period for estimation purposes)

NG Reformer	20	100	140	45	18,500
NG Reformer	50	500	210	50	130,000
NG Reformer	100	400	340	55	158,000
Total for Period		1000			306,500
Grand Total		**1,115**			**339,125**

This indicates an average station cost of approximately $304,000 over the entire period, with an average daily vehicle capacity of about 60-65 per station (i.e., one dispenser). At an average of 8 days between fills, theoretical maximum capacity would thus be approximately 1115 stations x 63 vehicles/day x 8 days = ~560,000 vehicles in use.

Gasoline Station Costs

If on-board gasoline reformers are to meet both automotive technical and economic requirements, they will require a "fuel cell grade" of gasoline. This gasoline would ideally have less than 2 ppm of sulfur (as opposed to average levels near 300 ppm today and 30 ppm proposed in new regulations), and would preferably have zero aromatics to reduce the likelihood of coking in the on-board reformer. While the oil industry could provide such a designer gasoline with relative ease, it would involve extra cost at the retail level. The gasoline station owner would have the option of substituting the fuel cell grade gasoline for one of the existing gasoline grades, or adding a new underground tank and dispenser system.

Either option would add costs. Substitution of a current grade would sacrifice revenue from existing cars. A medium station serving 175 cars per day might lose revenues of $230,000 per year at the wholesale level (excluding taxes) by forgoing one of three grades of gasoline. This assumes that the customer would not switch to a different grade if the medium grade were removed from a station.

Putting in a new tank and dispenser system might require capital investments of approximately $95,000 per station. While costs vary significantly from one region to another, particularly for installation, typical station costs for one new tank and dispenser are shown in Table 2. Thus the one-time capital costs for a new fuel cell grade gasoline tank and dispenser could cost less than the annual revenue loss giving up one grade of conventional gasoline.

Table 2. Approximate Cost of New Underground Gasoline Tank and Dispensing System

Component	*Cost (US$)*
10,000 gallon double-walled tank	10,000 to 20,000
Dispenser with nozzles and accessories	15,000
Electronic card reader	15,000
Pump, leak detection, plumbing, etc.	10,000
Installation	25,000 to 50,000
Total	$75,000 to $110,000

Methanol Station Costs

The fuel infrastructure investments should be similar for gasoline, methanol and ethanol. Since methanol has only half the energy density of gasoline, a methanol tank might have to be twice as large as the gasoline tank to support a given number of vehicles. However, an on-board methanol steam reformer should have somewhat higher efficiency than either an ethanol or gasoline reformer, say 80% instead of 65% for a gasoline or ethanol high temperature ATR type of reformer. In addition, the fuel cell running on methanol should have slightly higher efficiency due to higher hydrogen content, and the endothermic methanol reformer can more readily utilize the energy in the hydrogen that necessarily bypasses the anode of any fuel cell with dilute hydrogen mixtures. Finally, the methanol reformer's relative simplicity and compactness will result in less weight than expected in gasoline reformer systems, further improving the methanol vehicle's relative fuel economy.

As a result, a methanol FCV in the most probable case could have approximately 50% higher on-board fuel economy than a gasoline FCV. In this case the methanol storage at the fueling station would need to be only 33% larger than the gasoline storage. With best-case assumptions for both reformers, however, the methanol advantage shrinks to only 15%, so the methanol tanks would have to be 74% larger than the gasoline tanks to support the same number of FCVs. Taking an average, the methanol tanks would have to be 50% larger than the gasoline tanks.

However, tank cost does not scale with tank size, and a total fueling system includes more than just the tank as shown by Table 2. For example, a 10,000-gallon 10-foot diameter tank cost $20,310 in one quote, while a 20,000-gallon tank cost $30,040. A 50% large tank (15,000-gallon capacity) cost $24,600. Hence the cost increment for a 50% larger methanol tank would be 21% -- $24,600 instead of $20,310 or a net difference of only $4,300. Thus a methanol tank system might cost $100,000 compared to $95,000 for a gasoline tank system. The difference, however, is much less than the variation in costs between local fueling sites.

In addition, all underground tanks installed by the majors in California are double walled tanks compatible with methanol, so there should be no extra cost for methanol over gasoline tanks. The oil industry members will certainly have more detailed cost information to verify these estimates, and to confirm whether there are any additional costs of making the full refueling system compatible with either ethanol or methanol, both of which are excellent solvents that attack materials previously used in gasoline-only fueling hoses, meters and other devices.

Another less expensive option for methanol would be to install smaller aboveground tanks for the early market entry. Costs for a small above ground methanol tank, pump and dispenser could be in the $20,000 to $25,000 range. These tanks could be moved from one station to another, easing the early entry capital investment requirements. Thus a fueling station could add a 2,000-gallon aboveground methanol tank initially. Once methanol FCVs exceeded the capacity of the tank, the station could install a 10,000-gallon underground tank and sell the above ground tank to another station with a small FCV demand.

Ethanol Station Costs

Ethanol has a 34% higher energy density (LHV) than methanol, but still 34% lower than that of gasoline. But, unlike methanol, ethanol will suffer from many of the same fuel cell limitations as gasoline, since ethanol will require a very high temperature ATR/POX type reformer instead of the lower temperature methanol steam reformer. So no significant difference would be expected between ethanol and methanol fueling costs. It is therefore estimated that the cost of an average ethanol tank and dispenser system would be in the $100,000 range.

The conclusion is that the infrastructure costs for methanol, ethanol or gasoline would be similar – about $100,000 per station, plus or minus $25,000, or a total cost of $110 million for the 1,100 stations required in this scenario. Hence the hydrogen infrastructure would cost about five times more than the liquid fuel infrastructure to install.

Appendix

E Fueling Station Infrastructure Cost Analysis

Stefan Unnasch

Arthur D. Little, Inc.

Objective

A model of fueling station costs was developed in order to evaluate the parameters that affect the cost of fueling station operation price of fuel for FCVs. The purpose of the model was to provide an understanding of the parameters that affect fuel price and vehicle operating cost. This study investigates the obstacles and barriers to commercializing FCVs. One such is the availability and cost of infrastructure (for FCV fuels other than future pump grade gasoline).

Producing 40,000 FCVs per year will require sales to the general public who will expect adequate fuel availability. In order to provide sufficient fueling outlets for FCVs, fueling station construction must proceed while small numbers of FCVs are initially on the road. The requirement to provide fuel and make customers feel comfortable with purchasing FCVs will result in higher costs per unit fuel than fuel sales in a mature market.   The analysis in this Appendix is primarily aimed at identifying the magnitude of the cost during this early transition period.

The results presented here should not be interpreted as an evaluation of the profit potential or business case for any fuel. Evaluations of fuel and fueling station cost include the following:

- Determine extent of investment in infrastructure during the transition to large volume vehicle production
- Examine payback and scenarios
- Examine sensitivity to taxes, wholesale fuel price, transportation cost, equipment maintenance, vehicle fuel economy, number of fueling stations, vehicle sales rate, baseline gasoline vehicle fuel economy, baseline gasoline retail price, etc.
- Provide framework for discussions over risk sharing

Fueling Station Cost Inputs

A strawman estimate of fueling station costs was made for each fuel. Cost estimates were based on the following principles:

- Equipment costs are consistent with modestly optimistic expectations for fueling equipment
- Fueling station costs are allocated between FCVs and conventional vehicles in the same manner for all fuels
- Non-fuel-specific assumptions (vehicle sales, interest rates, number of vehicles, miles driven, etc.) are the same for all fuels.
- Initial assumptions on wholesale fuel prices, equipment maintenance, and other fuel-specific parameters were adjusted as needed (within still-reasonable ranges of values) to yield a positive upward trend in cash flow within approximately one year after the 40,000 v/yr milestone is reached in California, reaching positive annual cash flow within 3-4 years thereafter.

Cost components were estimated for the categories shown in the following table.

Cost Category	*Component*
Capital	Fuel storage Local reformer for hydrogen Dispenser Installation
Debt Service	Interest Capital recovery
Fuel	Wholesale fuel Storage Taxes Distribution
Operation and Maintenance	Station overhead Station labor Equipment maintenance Certification costs

Special cases are noteworthy for gasoline and ethanol, as follows.

- In the case of gasoline, a dedicated fueling infrastructure was analyzed, under the assumption that a special refinery product such as naphtha may be required. However, if operating FCVs on future lower sulfur gasoline proves feasible, that alternative would require no fueling station infrastructure investment.
- In the case of ethanol, the infrastructure analysis assumes a limited fuel-flexible option in which all stations could be equipped to vend ethanol as well as gasoline or naphtha. Since usage of the ethanol option is expected to be very light except in a gasoline availability or price squeeze, the study assumes only 10 percent as many fueling stations would be modeled with ethanol as would be the case for the other fuel cell fuels. This ethanol flex-fuel scenario is compatible with a zero sulfur naphtha infrastructure, including the on-board reformer.

Capital Costs

Liquid fuels: Capital costs for liquid fuels (except conventional gasoline) include the installation of an underground storage tank or tank conversion, underground piping, and dispenser. Approximately 70% of the stations were assumed to require a new tank. The typical equipment is intended to provide capacity for one or two fueling dispensers at a retail fueling station, although only one was assumed to be installed per station until after the 40,000 v/yr sales milestone. Additional dispensers could be added as fuel cell vehicle population increases.

The following cost estimates were made for liquid fuels. Fueling station costs are based on estimates published by EA Engineering and are consistent with experience with fueling facilities constructed as part of the California M85 program. The costs include installation contractor and equipment.

Component	*Cost*
New storage tank and single dispenser	$93,600
Existing storage tanks with new dispenser	$46,500
Additional dispenser for added vehicle capacity	$28,800

Sources: EA Engineering
Sawyer, J. “Methanol Fueling Station Equipment Requirements,” APTA Alternative Fuel Bus Meeting, Tacoma, 1989.

Site-specific design costs are minimal assuming a no-frills installation. Station owner labor and overhead for procurement and supervision are not included. Fueling station costs are site specific. Integration with an existing fuel island is more costly than locating a storage tank and dispenser in a remote location of a fueling station. Fueling station costs can run as high as $100,000 for complex designs or situations with a high water table. This analysis assumes that fuel providers will find innovative ways to integrate fuel cell fueling equipment with station upgrades.

Hydrogen: Capital costs for hydrogen fueling stations are based on estimates from DTI (See Appendix D). The estimates were adjusted upward by the study team based on further information provided by reviewers. For natural gas reformer systems, cost projections in Appendix D are $210,000 for a 100 vehicle per day station for the first 500 units installed. In this study's revised estimate, a natural gas-based reformer fueling station that would serve approximately 50-75 vehicles per day (i.e., one dispenser) was assumed to cost $450,000. Even this cost estimate represents a fairly aggressive reduction in hydrogen fueling equipment cost. These estimates also require future commercial scale production of fueling components and are consistent with forward looking projections made by Shell.

Multi-Use Energy Stations: The use of a limited number of "energy stations," which combine onsite fuel cell power generation with hydrogen production for that fuel cell as well as vehicle refueling, was also considered. The costs assignable to FCVs for the energy station were estimated to be lower than for a dedicated FCV system, because some of the capital cost of the (somewhat larger) reformer is allocated to its power generation function. The specific details of the energy station costs were not analyzed. The allocation between capital costs for hydrogen production and energy production requires substantial further analysis and was not undertaken in this study. The potential advantages of the Energy Station concept indicate that such an analysis should be done.

Station capacity upgrades: For future hydrogen fueling station additions as well as capacity additions to existing fueling stations, the cost per new dispenser and upgrade to reformer and compressor capacity was assumed to be $220,000. These were assumed to accommodate an additional 60 vehicles per day, although none were included in this study's analysis until after the 40,000 vehicles/day sales milestone had been reached. The cost of hydrogen fueling equipment is an important variable in the overall cost of hydrogen fueled vehicles and should be explored in further sensitivity analyses.

Component	*Cost*
NG reformer 50 vehicles/day	$450,000
Hydrogen production at energy station	$300,000
Additional dispenser for added vehicle capacity	$220,000

Sources: Thomas, S. (Appendix D) adjusted upward to reflect site specific modifications, comments from study team members and other reviewers, and higher costs during transition to large volume production

Upstream infrastructure: Some additional investment will be required for production and delivery of special FCV fuels to the station sites. This study takes the position that such upstream costs will be small in relation to the station costs and will be recovered "by the yard" in the estimated price components for each fuel, as shown in the fuel-specific tables in this Appendix and the individual fuel chapters. Accordingly those costs are not included in this infrastructure analysis to avoid double-counting.

Operating Costs

Fueling Station Overhead: Operating costs include equipment maintenance and each fuel dispenser's share of the costs for operating and maintaining the fueling station site. The station site costs were allocated between fuel sales and convenience store sales. The following assumptions provide the basis for estimating a fixed cost per pump that should be applied to FCV fuel. The same rent cost per dispenser was assumed for all fuels.

During the transition period, the analysis is based on FCV fuel outlets located at existing gasoline fueling stations. Initially, only one dispenser would provide FCV fuel. While some fuel options may require more space at a fueling station, the fixed rent assumption is consistent with the conventional gasoline fuel sales (per pump) not being affected by adjacent FCV fuel sales. The compatibility of multi-fuel sales would need to be evaluated on a case-by-case basis.

Assumed Baseline Gasoline Station Operations—Typical Station

Assumed quantity	*Units*
140,000	gal/month
17,284	fills/month
576	fills/day
4	fills/pump/hr
8	pumps/station
8.1	gal/fill
67	fills/yr/vehicle
5.45	days/fill/vehicle
392	vehicles/pump
18	hours of operation per day
$ 0.07	operating margin/gal
$ 0.02	capital amortization
$ 0.09	total margin

Assumed Baseline Gasoline Station Costs—Typical Station

Assumed quantity	*Units*
$ 10.00	station operation labor cost/hr
Monthly Costs:	
$ 5,400	onsite labor
$ 9,000	site rent
$ 800	utilities
$15,200	total monthly cost
50%	fuel share of monthly cost
$ 7,600	fuel share/month
$ 933	equipment O&M
$ 8,533	OH + O&M/month = fuel share of total operating cost
$ 0.061	station operating cost/gal

Includes landscaping and site maintenance

Competition with Conventional Vehicles

Competition with gasoline was assumed to be the basis for determining the price of FCV fuel. Fuel costs were therefore assumed to be the same as for a gasoline HEV per mile. The gasoline HEV was estimated to have the same size and attributes as an FCV with hybrid operation resulting in a 25 percent improvement in fuel economy over a conventional ICEV.

While hybrid electric operation may result in more than a 25 percent improvement in fuel economy, this study seeks to determine a benchmark fuel cost that consumers will find to be favorable when shopping for a car. Consumers may not be presented with exact side-by-side replicas of FCVs and HEVs. If such identical vehicles were made, the consumer may have a higher fuel economy expectation for the FCV.

The following table illustrates how an FCV fuel price is calculated for comparison with an HEV. Cost components of a baseline gasoline price are shown in the table. These values are consistent with regular gasoline prices in California. The price of gasoline is a key factor affecting the economics of FCVs; further exploration with a sensitivity analysis is beyond this study's scope but recommended in the framework of the economics presented here.

Retail Gasoline Price

Estimated value	*Cost component*
$ 1.07	Wholesale gasoline
$ 0.02	Bulk Storage
$ 0.05	Truck Transport
$ 0.184	Fed Tax
$ 0.18	CA Excise tax
$ 0.09	Retail Gasoline Margin
$ 0.10	CA Sales Tax
$ 1.70	Retail Pump Price

Baseline gasoline vehicles used in these calculations achieved 45 mpg. This relatively high fuel economy is consistent with the greenhouse gas comparisons made in the study. The lightweight, high fuel economy vehicles were selected in order to provide an analysis where FCVs would be certain to meet greenhouse gas emission goals. FCVs that achieve the higher fuel economy projections discussed in Appendix B would require less fuel and be more competitive with conventional gasoline vehicles. Larger vehicles could also be fuel cell powered. Their greater fuel consumption would affect fueling station economics.

	Fuel economy	*$/mile*
Gasoline ICE	45	$ 0.038
Gasoline competition (HEV)	56.25	$ 0.030

The combination of FCV fuel economy and competitive fuel price ($/mi same as a gasoline HEV) determines the required FCV fuel price. The required fuel price was determined for each fuel based on benchmark vehicle efficiency values. Estimates of the wholesale fuel price, combined with tax, and transportation were used to estimate the available gross sales margin for each fuel. These values are presented later for each fuel.

Fueling Station Cash Flow Model

A model of fueling station cash flow was developed for each fuel type. The available revenue for selling fuel cell fuel was based on the principle that the FCV customer should be required to pay no more for fuel than a user of a similar gasoline HEV. An "allowable fuel price" is calculated to be $0.030 cents/mile. This value is represented in $/gallon or $/lb of fuel cell fuel.

Various analysts indicate that the fuels considered in these studies have the potential for FCV operation. The analysis in this appendix does not attempt to examine all of the circumstances where a fuel may be successful but rather determines the cost of a transition to large volume sales.

The infrastructure costs are determined for each fuel over a 10-year period (including early pre-pilot testing, the pilot phase, and an assumed five years after market introduction) as vehicle sales ramp up to 40,000 per year. These amounts include the cost of fueling station equipment and costs related to operating the fueling station. The total cost of the transition is represented as the sum of the capital purchases and operating costs minus the "margin" that is available based on the customer paying $0.03/mi. The sum of capital and operation minus margin are presented as a simple sum over a 10-year period as well as on a net present value basis.

The analysis for liquid fuels includes existing state and federal excise taxes (road tax) specific to each fuel. The calculations for hydrogen are presented with a hypothetical zero excise tax.

Fueling station operation costs, fueling frequency, interest rates, and other parameters are kept the same in each set of calculations. However, each cash flow analysis is constructed to present a situation in which the cash flow becomes positive after approximately ten years. The assumptions on wholesale fuel price have the most significant impact on the cash flow. The basis for the values used for wholesale fuel price (input from fuel providers and direct project experience) varies among the fuels as the primary goal was to construct a scenario in which the fuels could be economic, with reasonable assumptions, rather than to prove that every fuel could be successful.

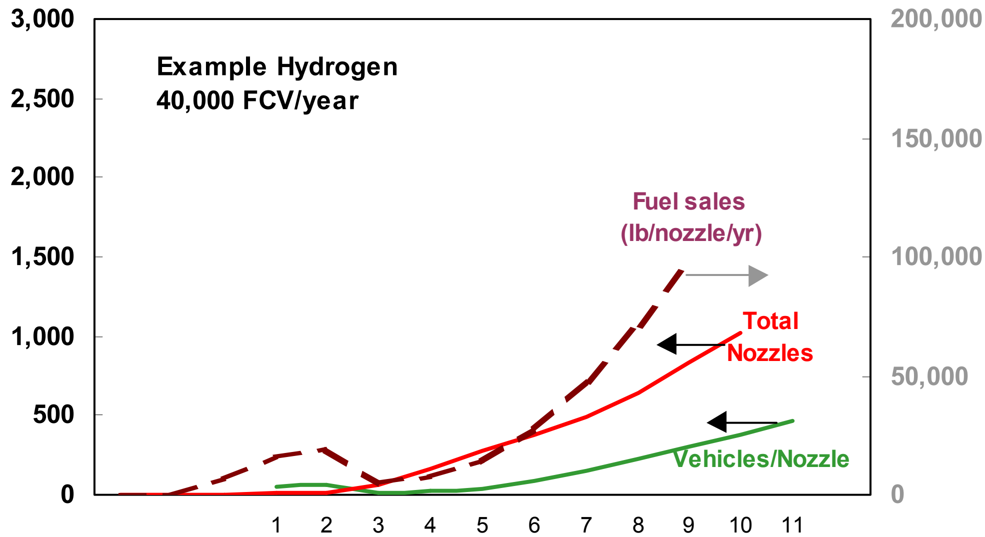
Parameters that were calculated are shown in the following table. The numbers of fueling stations and additional dispensers were assumed the same for each fuel except ethanol, where the value was 10% of the others to illustrate a fuel flexible strategy. Significant parameters that do not depend on fuel type were held constant for all fuels.

Fueling station cash flow was estimated from the “residual cash” for each fuel. This residual is the cash remaining from fuel revenue (at gasoline-equivalent prices on an average per-mile basis) after taxes and all non-station costs have been paid. Operating and capital costs were deducted from the residual to provide an annual cash flow estimate for each fuel. In the first several years, this cash flow is negative for all fuels.

Parameter	*Comment*
Annual vehicle sales	3,000 in first year of sales and 40,000 in 4th year (3rd & 7th years after decision to commercialize)
Total vehicles	Summation based on accelerating rate of annual sales, yielding 72,000 in Year 7 and nearly 800,000 in Year 12, all net of retirements
Retired vehicles	Retired after 8 years
Upstream infrastructure	Included in delivery price
Total pumps	Aim for 4 fuelings/pump/hr (but this is a derived value and does change somewhat each year)
Total stations	500 within four years after market introduction, with continued rapid additions afterward
Liquid fuel transportation	$0.05/gal (actual gallon)
Annual infrastructure capital, k$	Depends on fuel (see earlier section)
Capital debt balance, k$	Pay off 8%/yr through year 7, 10% afterward/year
Infrastructure financing, k$/yr	Pay 8%interest on capital balance/year
Fuel sales (gal/nozzle/month)	Depends on no. of vehicles and fuel economy
Fixed station overhead	$950/pump/month
O&M, k$/month	Depends on fuel: 2% of installed capital/yr
Marketing, k$/month	0.05% of fuel sales
Annual fueling station cost, k$/yr	Overhead + O&M + Financing + Capital recovery
Residual cash, k$/yr	Fuel sales x residual/gallon (or lb)
Net cash flow, k$/yr	Residual available from revenue – AFSC Cost

Vehicle Fueling Station Construction

The following figure illustrates the parameters that relate to vehicle fueling. The pace of fueling station construction is limited in the analysis to 150 new fueling stations per year. The rate of fueling station construction represents an estimate of the practical limit on construction and permitting efforts. During the initial introduction of FCVs, fuelings per hour increase to 2.8 within the 7th year after the beginning of the pilot phase. Lower rates of fueling station nozzle utilization result in lower revenues per nozzle as reflected by the annual cash flow. However, as the growth in FCVs is maintained, the vehicles supported per nozzle will increase unless the rate of fueling station construction is increased. As a practical implementation strategy, fuel providers may prefer to focus on installing more nozzles at existing stations. The decision to invest in additional fueling infrastructure would need to be coordinated with expectations for FCV sales.



Fueling Station Costs

The assumptions and results for the fueling station cost model are presented here for each fuel. The results are quantified in terms of total investment through the 40,000 v/yr milestone point on a cash cost basis and on a net present value basis (NPV) over a 7-year transition period. These results can be used as a basis for further discussions between stakeholders on defining strategies to minimize the risks for FCVs and infrastructure.

Notes on input sensitivities

- With excise tax of $0.364/equivalent gallon or $0.16/lb, cash cost and NPV become $241,085 and $151,956 respectively.
- If all other assumptions are held constant and natural gas feedstock costs were $8/MMBtu, cash and NPV become $243,400 and $153,400.

Hydrogen economics are sensitive to the capital cost for the fueling station, price of gasoline, reformer efficiency, natural gas price, and electric power price. Any of these assumptions has a substantial effect on the positive cash flow for hydrogen fueling. The expense for financing fueling station capital and pay off of capital represent a substantial portion of the net cash flow for hydrogen fueling. A substantial retail hydrogen residual margin is estimated based on the assumptions for HFCVs. This margin must ultimately cover the cost of hydrogen fueling equipment.

Hydrogen Fueling Station Costs

Parameter	*Value*	*Units*
Gasoline subcompact fuel economy (FE)	45	mpg
Benchmark competitive HEV	56.25	mpg
Benchmark HEV energy efficiency ratio (EER)	1.25	Btu/Btu
FCV EER	1.96	Btu/Btu
FCV FE	40.1	mi/lb
Retail gasoline	1.70	$/gal
Benchmark operating cost	3.0	c/mi
Estimated FCV retail residual for capital cost, etc.	$0.46	$/lb
Allowable hydrogen fuel price	**$1.21**	**$/lb**
Capital Costs		
CH_2, 50 cars/day	$450,000	
Energy Station	$300,000	
CH_2, Added Capacity/nozzle	$220,000	
Capital plus cash flow*	With tax	No tax
Cash Cost ($000)	$238,872	234,700
Net Present Value ($000)	$148,000	127,564

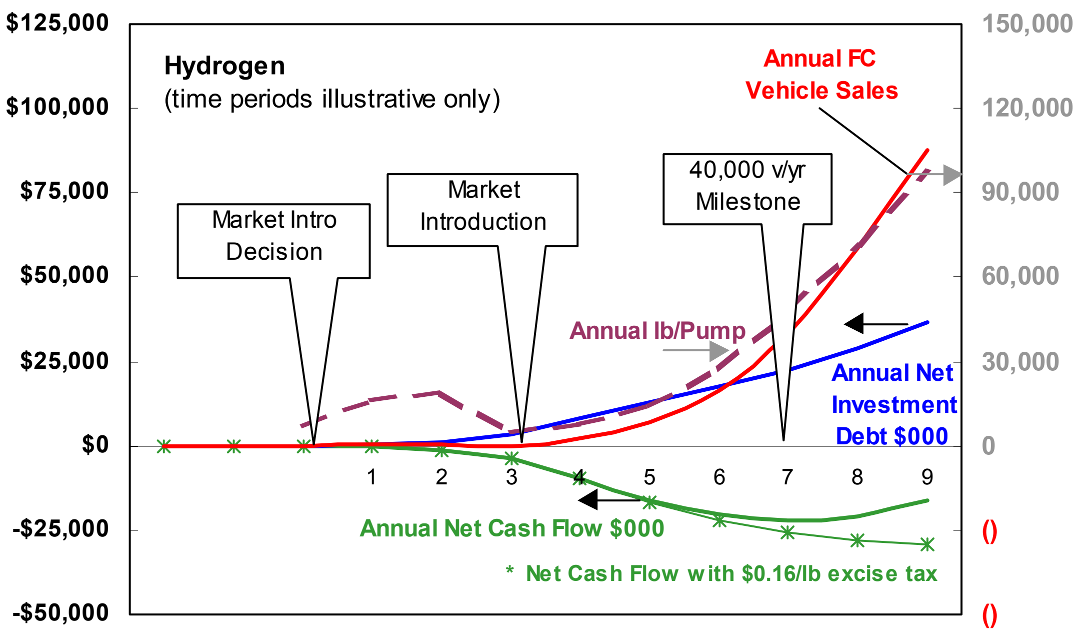
*First 10 years after decision to introduce FCVs to market (8 after market intro)

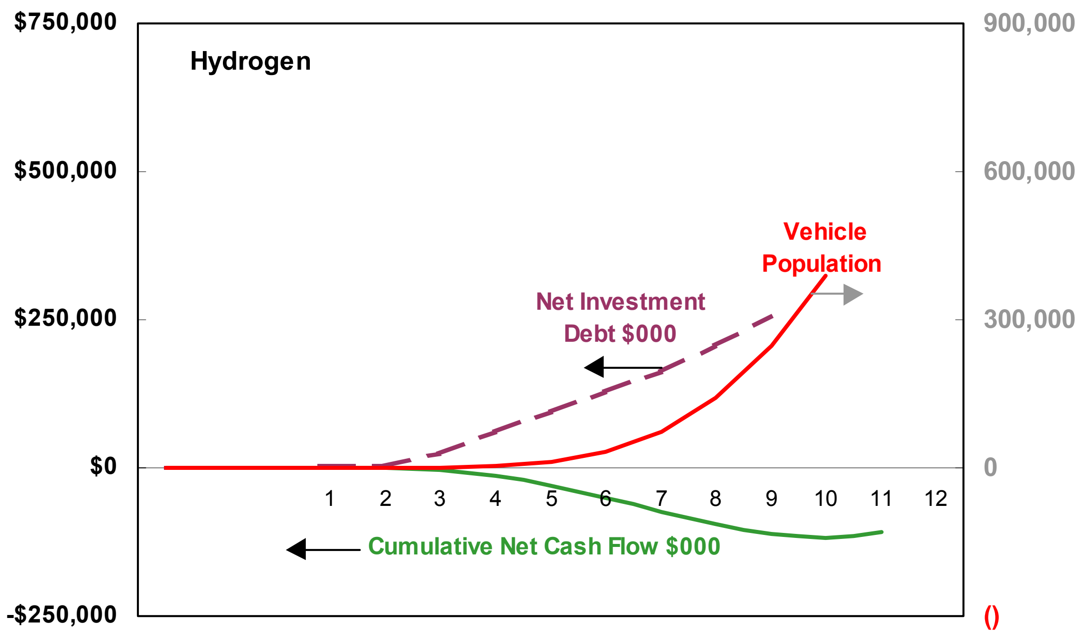
The price of natural gas has a very significant impact on cash flow for the hydrogen fueling station. Some analysts suggest that higher natural gas prices will prevail in the future as supplies become limited in the U.S. If natural gas prices were to reach and remain at $8/MMBtu, a positive cash flow situation is not achieved with the other assumptions in this analysis.

No state or federal excise taxes are included for hydrogen. This tax treatment is a built in subsidy for this fuel that is available today. The outlook for future taxation is undetermined. The net cash flow is also shown for a hypothetical excise tax of $0.16/lb or $0.364/equivalent gallon, which is the same as the gasoline excise tax rate. The additional excise tax reduces the net cash flow. However, in the early transition period, the negative net cash flow is dominated by the financing and capital pay off costs for the refueling equipment. The excise tax becomes a noticeable fraction of the cash flow only when significant numbers of HFCVs operate on the road.

Fuel Cell Fuel Parameters -- Compressed H_2

Cost level	*Cost component*
$ 5.50/MMBtu	Natural gas price at refueling site
$ 0.48/lb	Natural gas (70% efficiency HHV)
$ 0.17/lb	Compression
$ 0.65/lb	Wholesale price
$ ---	Bulk fuel storage terminal
$ ---	Truck transport
$ ---	Federal tax
$ ---	CA excise tax
$ 0.46/lb	Retail hydrogen residual margin for capital, etc.
$ 0.09/lb	CA sales tax
$ 1.21/lb	**Retail hydrogen pump price**





<u>Methanol</u> economics data displays begin on the following page.

Methanol Fueling Station Costs

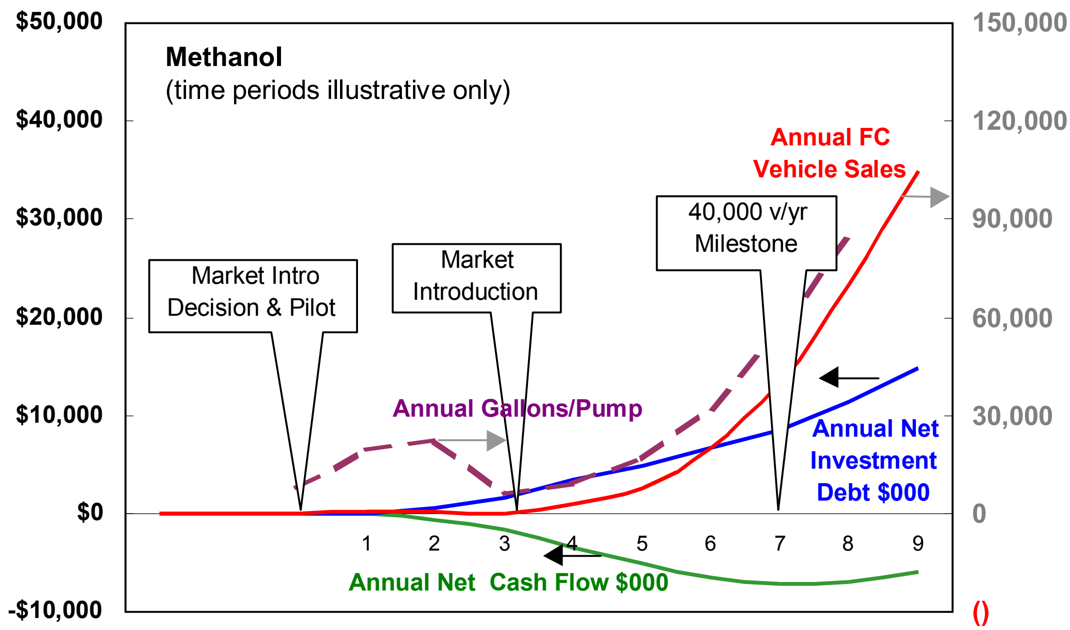
Parameter	*Value*	*Units*
Gasoline subcompact FE	45	mpg
Benchmark competitive HEV	56.25	mpg
Benchmark HEV EER	1.25	Btu/Btu
FCV EER	1.5	Btu/Btu
FCV FE	33.9	mpg methanol
Retail gasoline	$1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Allowable methanol fuel price	$1.03	$/gal methanol
Estimated FCV retail residual for capital, etc.	$0.13	$/gal methanol
Capital costs		
New station with tank	$93,600	
Retrofitted existing tank	$46,500	
Added pump	$28,800	
Capital plus cash flow	Through 40K v/yr:	
Cash cost ($000)	$57,918	
Net present value ($000)	$31,400	

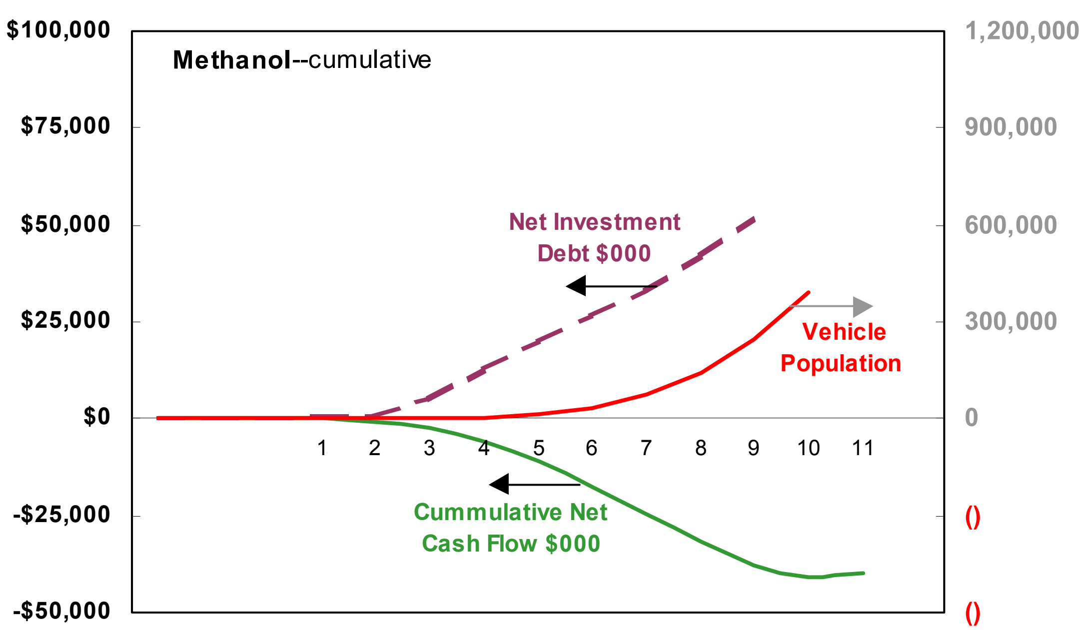
Note: If excise tax is zero, retail margin increases to $0.30/gal methanol. Cash cost becomes $50,800 or $27,500 on NPV basis.

Fuel Cell Fuel Parameters – Methanol

Estimated cost	*Units*
$0.38 /gal (MeOH)	Bulk fuel cost
$ 0.15 /gal	Bulk fuel margin
$ 0.05 /gal	Bulk fuel transport
$ 0.58 /gal	Wholesale price
$ 0.02 /gal	Bulk fuel storage terminal
$ 0.05 /gal	Truck transport
$ 0.093 /gal	Federal tax
$ 0.09 /gal	CA excise tax
$ 0.06 /gal	CA sales tax
$ 0.13 /gal	Retail methanol residual for capital cost, etc.
$ 1.03 /gal	**Retail methanol pump price**

Methanol economics are sensitive to the price of methanol and gasoline. The methanol prices used in this analysis are based on price projections from the methanol industry. These prices result in a trend towards positive cash flow once vehicle sales exceed 40,000 per year.





Gasoline Fueling Station Costs

A. Naphtha

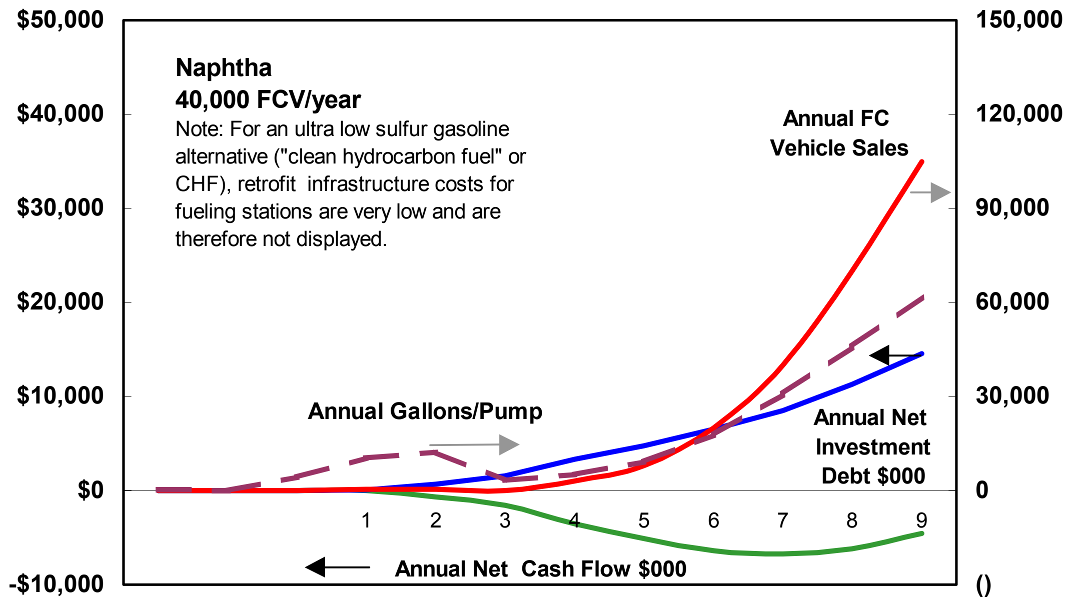
Parameter	*Value*	*Units*
Gasoline subcompact FE	45	mpg
Benchmark competitive HEV	56.25	mpg
Benchmark HEV EER	1.25	Btu/Btu
FCV EER	1.39	Btu/Btu
FCV FE	62.6	mpg
Retail gasoline	$1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Allowable fuel cell fuel price	$1.89	$/gal
Estimated FCV retail residual for capital, etc.	$0.25	$/gal
Capital costs: New station with tank	$93,600	
Retrofitted existing tank	46,500	
Added pump (later)	$28,800	
Capital plus cash flow	Thru 40K v/yr milestone	
Cash cost ($000)	$58,10057,212	
Net present value ($000)	$31,40036,532	

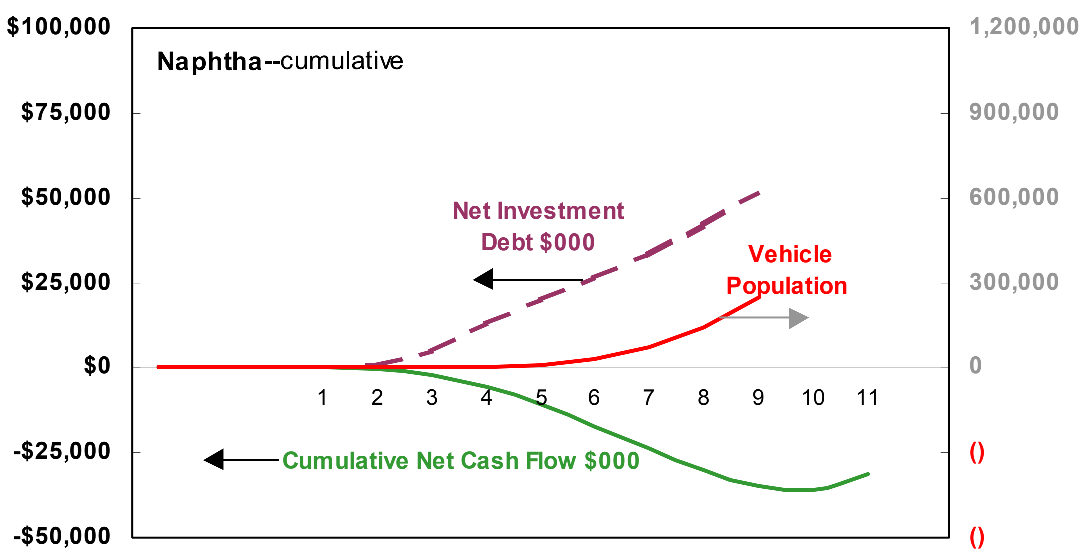
Note: If excise tax is zero, retail margin increases to $0.59/gal naphtha. Cash cost becomes $49,600 or $26,900 on NPV basis.

Fuel Cell Fuel Parameters – Naphtha

Estimated amount	*Cost component*
$ 1.07	Wholesale price
$ 0.02	Bulk fuel storage terminal
$ 0.05	Truck transport
$0.184	Federal tax
$ 0.18	CA excise tax
$ 0.25	Retail naphtha margin
$ 0.12	CA sales tax
$ 1.89	**Retail naphtha pump price**

The analysis shown here reflects a dedicated fuel cell infrastructure. Wholesale fuel cell naphtha prices are assumed to track wholesale gasoline prices. The economics of this fuel option are not very sensitive to gasoline prices. However, in periods of low gasoline prices, fueling station operators experience reduced margins and reduced revenues. The reduced revenues can affect the ability of fueling station operators to obtain credit.





Ethanol Fueling Station Costs

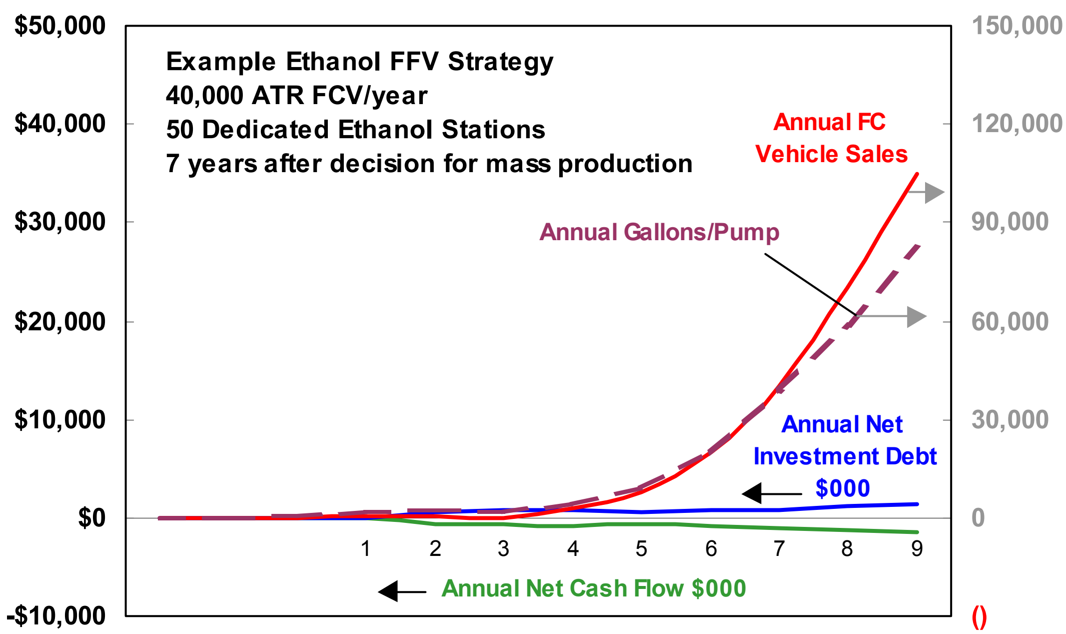
Parameter	*Value*	*Units*
Gasoline subcompact FE	45	mpg
Benchmark competitive HEV	56.25	mpg
Benchmark HEV EER	1.25	Btu/Btu
FCV EER	1.39	Btu/Btu
FCV FE	46.5	mpg
Retail gasoline	$1.70	$/gal
Benchmark operating cost	3.0	cents/mi
Est. FCV retail residual for capital, etc.	$0.04	$/gal
Allowable fuel cell fuel price	**$1.42**	**$/gal**
Capital costs		
New station with tank	$93,600	
Retrofitted existing tank	$46,500	
Added pump	$28,800	
Capital plus cash flow (50 stations only)	Thru 40K v/yr milestone	
Cash cost ($000)	$7,949	
Net present value ($000)	$4,435	

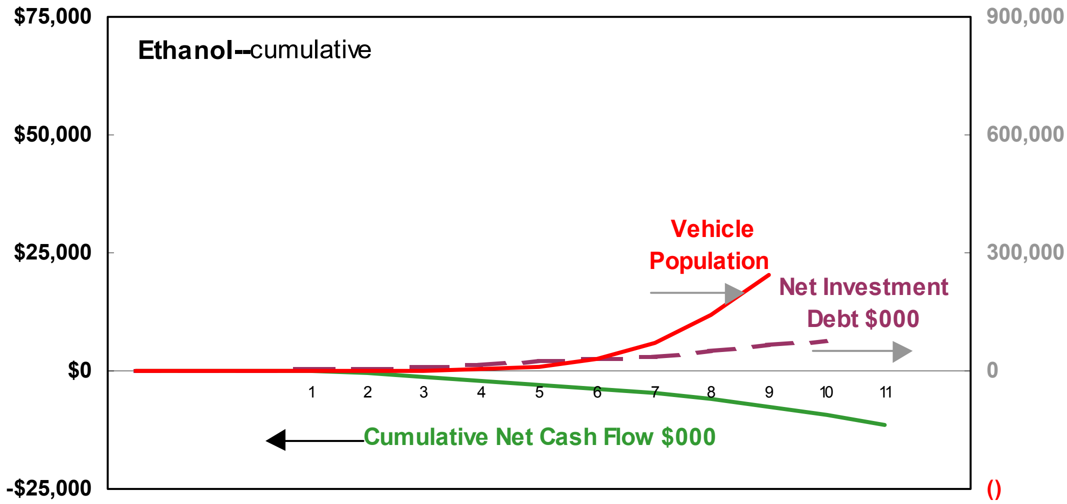
Fuel Cell Fuel Parameters – Ethanol
(Assume limited near term volume)

Estimated value	*Parameter*
$ 1.35	Wholesale ethanol
$-0.42	Federal tax credit, small producer credit
$ 0.02	Bulk storage
$ 0.05	Truck transport
$ 0.123	Federal tax
$ 0.12	CA excise tax
$ 0.09	CA sales tax
$ 0.08	Retail ethanol residual for capital cost, margin, etc.
$1.413	**Retail ethanol pump price**

Note: net negative cash flow would be even greater without tax credits. Accordingly, ethanol sales are assumed to be limited as a flexible fuel strategy that can be changed quickly if fuel market conditions change.

The scenario for ethanol assumes a limited and arbitrary number of fueling stations (50), for illustrative purposes only. The wholesale ethanol price is below current market prices but above the production cost for many producers. The federal tax credit for ethanol fuel as well as the small producer credit is available to reduce the cost of ethanol. These credits are subject to income tax and are not valued as highly as the $0.53 federal tax incentive for blends of ethanol and gasoline. If gasoline prices were to rise, ethanol sales would be more profitable; however there would be competing uses for ethanol as a blending component in gasoline. The analysis shown here does not show a positive cash flow for ethanol; however, a limited amount of fuel would be sold. Fuel providers would be postured to take advantage of higher margins if gasoline prices were to rise.





Sensitivity Analysis

Cash flow scenarios were determined for each fuel cell vehicle option. The assumptions that affect the cash flow illustrated in the above charts are presented here in a qualitative manner. The effect of changing each parameter on the cash flow for each station is indicated by the year of positive cash flow (PCF). While this value varies with each fuel, the qualitative description indicates the trend. Some of the most important parameters are the cost of fueling station equipment, the wholesale price of gasoline, and the wholesale price of the FCV fuel.

The analysis was based on FCV customers being willing to pay the same fuel price as a gasoline HEV with 25 percent improvement in fuel economy over a conventional gasoline vehicle. If customers can be convinced to pay more for the FCV fuel without risking public perception of the fuel option, the cash flow situation during the transition would improve. Similarly, if customer expectations were that they could be buying an HEV with even better fuel economy than assumed here (EER =1.4), the effect on the "retail residual margain" would be significant. One of the advantages of FCV fuels and their differentiation from pump gasoline is the potential ability to charge a premium for the fuel. While competition may erode pricing power in the long term, FCV fuel retailers hopefully can recover at least the same fuel cost per customer as they would with gasoline. Improved fuel economy from HEVs or FCVs that operate on pump gasoline provide a challenge for gasoline retailers as the same customer buys less fuel but makes essentially the same number of trips to the fueling station.

The size of FCVs also has an impact on the revenue potential for fueling stations. If FCVs were first commercialized in larger vehicle sizes, the potential fuel sales and revenue per dispenser would increase and improve the cash flow for the fueling station.

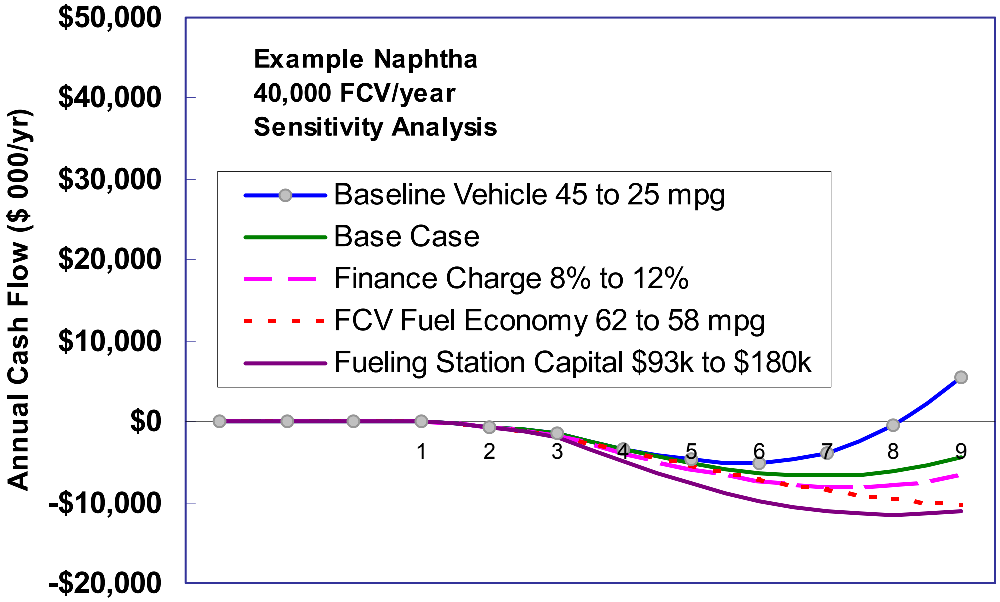
Another significant component of the transition costs are the "overhead" or fueling station costs for each dispenser. Lower overhead costs improve the cash flow situation significantly.

The cost of underutilized fueling capital is one of the most significant factors affecting the cash flow for FCV fuels (unless pump grade gasoline can be used). The effect of fueling station capital costs as well as the capital recovery factor (financing plus pay off of capital) is illustrated in the sensitivity analysis chart for Naphtha.

In summary, the cash flow situation for new FCV fuels is governed by revenues and costs. The most significant revenue factors include the ability to charge a premium for the fuel based on improved fuel economy and enough FCVs to generate substantial fuel sale volumes. The most significant factors that affect cost are the fueling station capital and the commodity price or wholesale price of fuels (or natural gas feedstock).

Estimated Results of Varying Key Economic Input Baseline Values

Parameter	*Alternative Value*	*Result*
Base vehicle fuel economy	Reduce to 30 mpg	More fuel sales, positive cash flow (PCF) 1 year earlier
FCV FE benefit	Increase HEV EER to 1.4	Lower FCV margin, PCF 2 years later
Fuel station overhead cost	Reduce to $200/nozzle	Depends on fuel, PCF 1-2 years earlier
Capital recovery factor	18% rate	Higher cost, PCF 1 year later
Fueling station capital cost	Increase	Later PCF, possibly never; depends on level and FCV fuel
State & federal excise taxes	$0.18/gal	PCF in 5 years for liquid fuels
Wholesale gasoline price	reduce to $0.80/gal	Later PCF; varies depending on FCV fuel



Example Naphtha
40,000 FCV/year
Sensitivity Analysis
Baseline Vehicle 45 to 25 mpg
Base Case
Finance Charge 8% to 12%
FCV Fuel Economy 62 to 58 mpg
Fueling Station Capital $93k to $180k
Annual Cash Flow ($ 000/yr)
$50,000
$40,000
$30,000
$20,000
$10,000
$0
-$10,000
-$20,000
1
2
3
4
5
6
7
8
9

Appendix

F Onsite Hydrogen Generation from Methanol

Sandy Thomas

Directed Technologies, Inc.

Background and Status

Previous analyses have assumed that hydrogen would be generated at the fueling site by reforming natural gas, or by electrolyzing water using grid electricity. However, the recent rise in natural gas prices in the US[19] suggests that other alternatives may provide lower cost hydrogen. For example, methanol might be used as an energy carrier to monetize stranded natural gas. The methanol would then be transported to the local fueling station where it would be converted to hydrogen for storage on-board the fuel cell vehicle. If the total cost of converting low-value stranded natural gas to methanol, transporting the methanol and then converting it in turn to hydrogen is less than the cost of converting higher cost domestic natural gas, then this approach might be worth pursuing.

The economic viability of this pathway depends on the potential cost of methanol delivered to a local fueling station, and the cost of the stationary methanol reformer system. The price of methanol might be low if it is made from low-cost stranded natural gas. And the cost of a stationary methanol reformer could be less than the cost of a natural gas reformer, since methanol is unique among common fuels with respect to reforming temperature: methanol can be reformed at 260^{o}C, while all other common fuels including natural gas require temperatures greater than 600^{o}C and often above 800 to 900^{o}C. Materials for the methanol reformer itself will cost less and will have less chance of damage due to hot spotting or thermal stress problems.

---

[19] Natural gas prices at Henry Hub reached the $5/MBTU level this summer, or twice the price that has prevailed for many years. California prices were several times higher temporarily.

DTI has previously analyzed this option under contract to the US Department of Energy[20]. This included reviews of both steam reforming (SR) and autothermal reforming (ATR) of methanol at the local fueling station, and compared the capital costs of these two methanol reformers with the cost of a steam methane reformer of the same size. The capacity of each reformer was 48 kg of hydrogen per day, enough to support a fleet of 60 fuel cell passenger vehicles assuming a 60% fueling station capacity factor. Since each FCV would refuel about once every eight days, this size-fueling appliance would refuel approximately 7 to 8 vehicles each day. Hence this is a very small fueling system by conventional gasoline station standards that handle on the average 125 cars per day and often over 200 cars per day. These initial fueling appliances would be used to accommodate market introduction of FCVs when small fleets of FCVs would be the norm.

Our detailed DFMA[21] costing analysis did show lower cost for the methanol reformers in mass production: $5,036 for the natural gas steam reformer, $4,792 for the methanol steam reformer, and $3,993 for the methanol ATR system. However, these savings were dwarfed by the costs of all the other hydrogen fueling appliance components, as shown in Table 1.

Table 1. Estimated mass production costs of hydrogen generators with 48-kg per day capacity.

	Steam Reforming of Natural Gas	Steam Reforming of Methanol	Autothermal Reforming of Methanol
Single Reformer Module	$763	$726	$605
6-module Reformer system	$5,036	$4,792	$3,993
Pumps & compressors	$1,584	$1,012	$1,380
ECU	$345	$345	$345
Housing	$1,390	$1,390	$1,390
Piping & misc. (10%)	$504	$479	$399
PSA	$2,670	$2,670	$3,500
H2 compressor	$4,684	$4,684	$4,684
Storage	$9,331	$9,331	$9,331
Dispenser	$4,846	$4,846	$4,846
Total capital cost	$30,389	$29,548	$29,868

DTI: Methanol reformer.XLS; Tab 'MeOH';D119 -10 / 20 / 2000

[20] C. E. Thomas, John P. Reardon, Franklin D. Lomax, Jr., Jennifer Pinyan and Ira F. Kuhn, Jr., *Distributed Hydrogen Fueling Systems Analysis*, prepared for the Hydrogen Program, Office of Power Technologies, US Department of Energy under grant No. DE-FG01-99EE35099, October 2000.

[21] DFMA refers to Design for Manufacturing and Assembly, a registered trademark of Boothroyd Dewhurst, Inc.

The historic average annual spot price of methanol delivered to the US Gulf coast is shown in Figure 1 over the last 17 years in both current and constant 1999 US dollars. The large spike in 1994 was due to a combination of the start of the oxygenated fuels requirement of the Clean Air Act Amendments of 1990, which required extra methanol to manufacture MTBE, and the outage of some methanol plants at the same time.

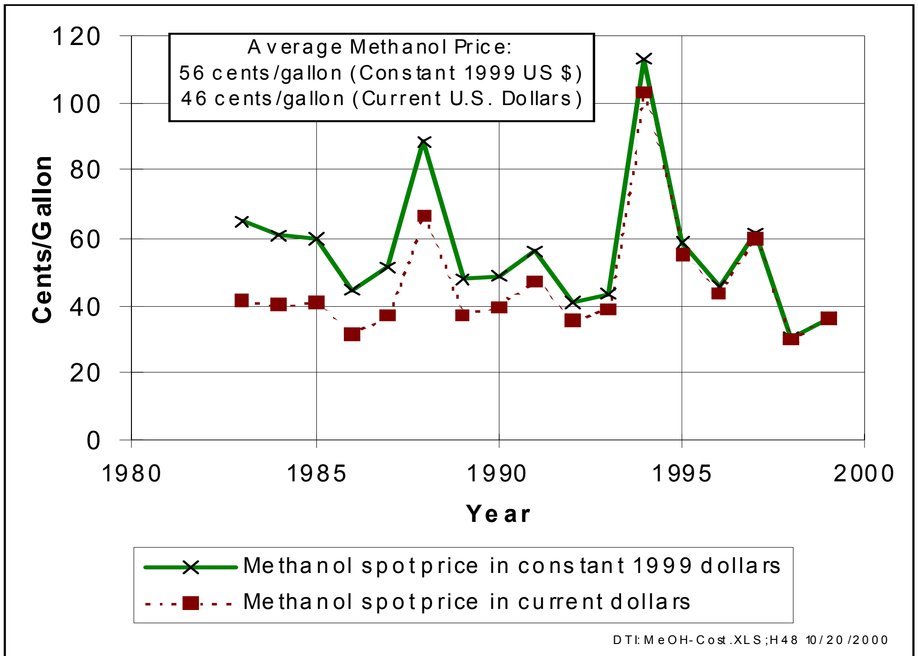


Figure 1. Annual price of methanol at the US Gulf Coast

The spot price of methanol has increased significantly since hitting record lows in 1998 and 1999, as shown by the monthly averages in Figure 2. The spot price of methanol reached a recent peak of 73 cents/gallon at the US Gulf in September 2000. Methanol price has averaged 56 cents/gallon at the US Gulf over the last 17 years in constant 1999 dollars.

The cost of methanol at the local fueling station must include costs for bulk storage, regional transportation and storage, and local transportation and storage. The assumed costs of transporting and storing methanol would be similar to the costs for transporting and storing gasoline – about 15 to 22 cents/gallon. The final delivered cost of methanol based on an average of the last 17 years would then be between 71 to 78 cents/gallon, which coincidentally is close to the spot price for methanol at the US Gulf in the last two months *before* adding regional and local transportation and distribution costs.

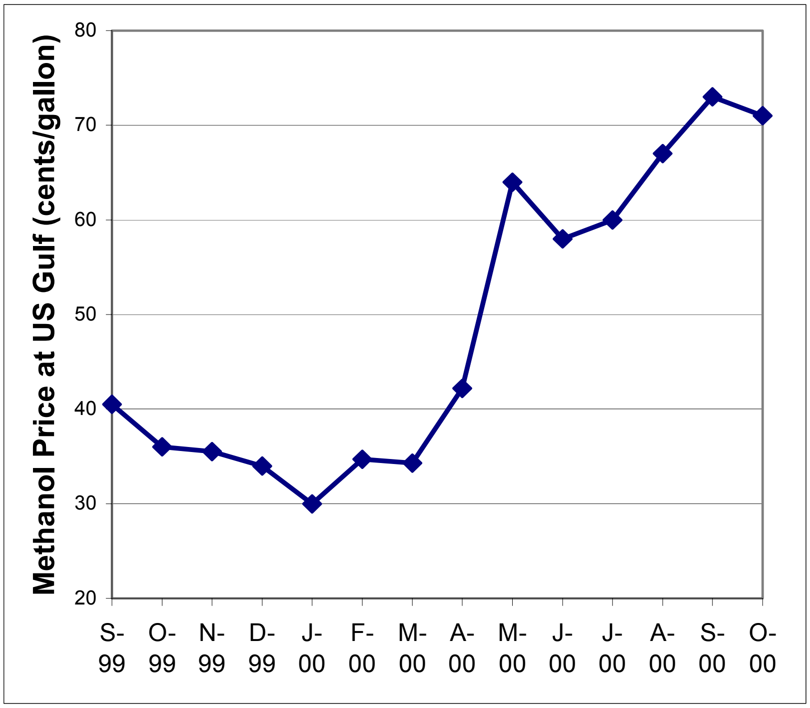


Figure 2. Recent monthly spot prices for methanol at the US Gulf

Combining this fuel cost of 75 cents/gallon delivered to the local fueling station with the fueling appliance mass production cost estimates yields the estimated cost of hydrogen in a mature FCV market, as shown in Figure 3. In this analysis it was assumed that natural gas is available at $6/MMBtu (HHV), much less than the per unit energy cost of methanol at 75 cent/gallon, which works out to $11.61/ MMBtu (HHV). This energy cost difference swamps the small advantage in fuel processor capital cost, even though the methanol reformer has higher efficiency than the steam methane reformer in this analysis (82% vs. 61.9%, LHV basis).

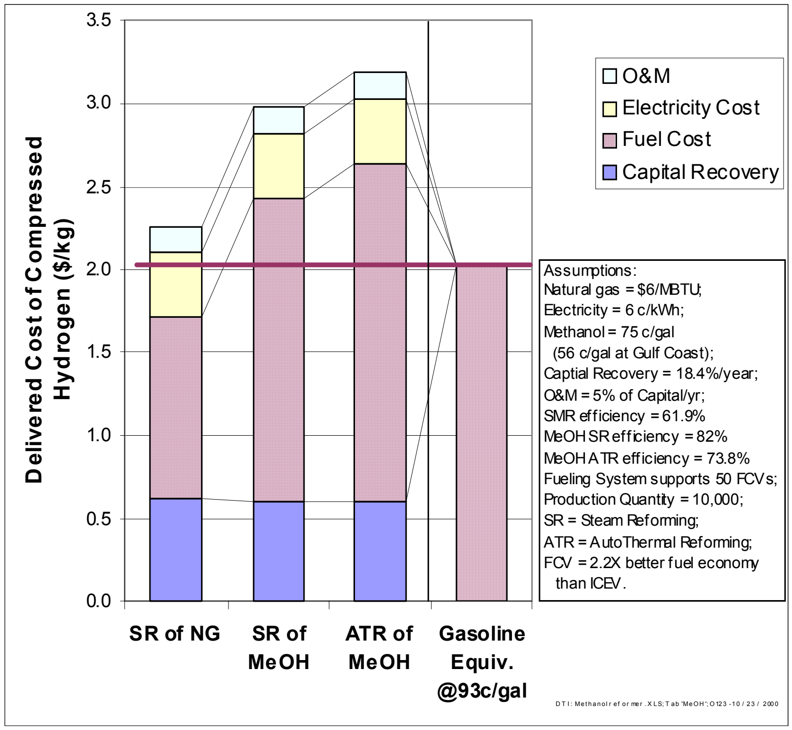


Figure 3. Estimated price of compressed hydrogen to yield a 10% real, after-tax return on investment

The bar on the right of Figure 3 represents the cost of hydrogen necessary to provide the FCV driver the same cost per mile as the driver of a conventional gasoline car of the same size, based on wholesale (untaxed) gasoline at 93 cents/gallon. In this case hydrogen would cost almost the same per mile as gasoline, even if hydrogen were taxed at the same rate per mile as gasoline.

This calculation assumes that the on-board fuel economy of the hydrogen FCV is 2.2 times that of a conventional gasoline ICE vehicle of the same size, which is the projected advantage for a mature direct hydrogen FCV on realistic driving cycles[22]. As shown in Figure 3, the projected cost of hydrogen from natural gas is close to the effective cost of wholesale gasoline under these circumstances, while hydrogen derived from methanol would cost 30% to 40% more. Costs of hydrogen from both methanol and natural gas would be less from larger hydrogen fueling appliances suitable for a mature FCV market refueling more than one hundred cars per day, although feedstock fuel costs of methanol or natural gas dominate hydrogen price.

---

[22] Current prototype direct hydrogen FCVs do not achieve this 2.2 advantage, due to the added weight and significant parasitic power consumed by current PEM fuel cell systems. This projected 2.2 to one fuel economy advantage for future lighter weight, lower parasitic load fuel cell vehicles on realistic customer driving schedules would be even higher, approximately 2.6 to one on the relatively lenient US EPA 55% city / 45% highway combined driving schedule

The calculation can also be reversed, to ask what price methanol would be required such that hydrogen made from methanol would cost the same as hydrogen from natural gas at $6/MMBtu. The required methanol price would be 41 cents/gallon for the methanol ATR system or 46 cents/gallon for the steam reformer. This would translate into a required methanol price at the US Gulf in the range of 22 to 27 cents/gallon. Referring to Figure 1, this price would be less than the annual average methanol spot price for any year since 1983. The lowest annual average available was 30.5 cents/gallon in 1998.

Rather than base the analysis on historical prices, one could speculate on the building of new methanol plants near sources of stranded natural gas. The American Methanol Institute estimates that a new 10,000 metric tonne per day methanol plant would cost about one billion US dollars. Assuming a 90% plant capacity factor, annual O&M costs equal to 5% of capital, a 30-year plant life and a required real, after-tax rate of return of 12%[23], then the capital recovery cost would be 19 cents/gallon (assuming 2.6% inflation and 26% marginal income tax rate that would require a 19.9% before-tax annual capital recovery rate). Assuming *free* natural gas but adding 4 cents per gallon for O&M and 7 cents/gallon for ocean transportation[24] would increase the US Gulf price to 30 cents/gallon, close to the 22 to 27 cent/gallon range to reach equity with hydrogen from natural gas. Given all the assumptions in this estimate, it is reasonable to speculate that methanol might be delivered at a price in the required range, but it would seem unlikely. Alternately, the price of domestic natural gas could increase well above the $6/MMBtu assumed here.

The methanol-to-hydrogen pathway would have one major advantage in a mixed-fuel vehicle market. If one or more carmakers built methanol FCVs while others built hydrogen-powered FCVs, then the fueling station could supply either methanol or compressed hydrogen. However, the study team was instructed for the purposes of this study to consider each fuel independently.

What needs to be done: Industry leaders need to decide whether the methanol conversion to hydrogen at the fueling station is a useful backup to the main pathway of converting domestic natural gas to hydrogen, given the estimate that hydrogen from methanol may cost 30% to 40% more than hydrogen made from domestic natural gas. If considered worthy of further development, then a planning activity should be instigated.

Why important to this FCV fuel alternative: the energy content of 2,300 bbl/day of C5/C6 is equal to that of about 550 ton/day of methanol, about 30% of the capacity of a current world-scale methanol plant. Spread over the output of all California refineries, this is a very small amount.

---

[23] We assumed a required real, after-tax return of 10% for domestic projects, but 12% from higher-risk foreign investments.

[24] Ocean transportation might be less from nearby nations such as Trinidad (2 to 3 cents/gallon) or Chile (4 to 5 cents/gallon), but in these cases natural gas would probably cost at least $1/MMBtu (HHV). This would then add about 8.6 cents/gallon to the cost of methanol (assuming 75% plant efficiency in converting natural gas to methanol), which would more than offset the lower methanol transportation cost from nearby nations.

Longer-Term Fuel Supply Implications

The 40,000-vehicle sales target implies a sales-growth trajectory that could yield 350,000 vehicles within five more years. The fuel requirement at that point would be about 4,500 bbl/day, 0.45% of the total gasoline production or 4.5% of the California refineries' C5/C6 naphtha isomerization capacity. This is still a minor percentage of refinery production. Scaling up with continued FCV sales growth would continue to require only a small share of the C5/C6 capacity for another decade or more past the 40,000 vehicles/year milestone.

Existing Models for On-Board Reformer Development

Steam reforming of naphtha to produce hydrogen is a well-developed process. Steam naphtha-reforming accounts for 13% of worldwide hydrogen capacity, mostly located in areas of low natural gas availability such as Japan, South Korea, and Europe. Steam naphtha reformers are more complex than steam methane reformers, and may require a fired feed vaporizer, a hydrodesulfurization reactor and a sulfur adsorber. The steam methane reformer requires only a sulfur guard bed. However, the point here is that this existing plant-scale process is a good starting point for the development of a fairly simple on-board reformer for the naphtha or C5/C6.

Similarly, there are several process vendors of C5/C6 light naphtha isomerization processes for octane enhancement. These processes include hydrogen treating and desulfurization, and could produce a suitable feed to a FC reformer.

Steam methane reformers which process feeds containing significant quantities of heavier components (e.g., propane, butane, pentanes, etc.) include a pre-reformer to convert these components to methane and CO_2 prior to feeding to the reforming section. During the period of low natural gas availability in the late-70s and early 80s, several 'rich gas' processes were used to convert naphtha to 'synthetic natural gas,' that is, to methane. These processes were reported to be able to handle feeds with boiling ranges of up to 420°F or 610°F and produce a gas suitable for steam methane reforming. SFA Pacific is not aware of any of these plants still operating today. Such a two-step process may not be practical for an FCV.

These considerations suggest that the C5/C6 stream is the most attractive candidate as a very low-sulfur and more easily reformed refinery-product alternative to gasoline for FCVs.

Appendix

G On-Board Hydrogen Storage Options

Robert Knight

Bevilacqua-Knight, Inc.

Introduction

Near-term hydrogen storage options include 5000 psi compressed gas, liquid, and hydrides; the compressed gas option is already well developed for general use despite its inherent drawbacks, LH_2 is usable but not widely considered practical, and hydrides are longer-term prospects. Research efforts are in progress to improve all three. This section provides further background information on these options beyond that included in Chapter 4 of the main report.

Compressed Hydrogen

Compressed H_2 must be stored in shapes without internal stress concentration points, historically in forged steel cylinders with spherical ends. Over the past decade, the typical upper natural gas service pressure of 3000 psi was increased to 3600 psi to improve NGV range, and in 1999 a 5000-psi standard was proposed for FCEV use. Although well beyond the range of ideal gas behavior and hence less efficient, the higher pressure provided increased range within the limited vehicle space available in FCVs.

Even this has severe limitations due to energy density, package shape, and number of tanks used, with a typical package ratio of about 7:1 versus gasoline in ICEVs. Larger diameters and conformable package systems help, but eventually 10,000-psi systems may be necessary—still leaving a 4.3:1 package ratio (Ijaz, 2000). One major U.S. automaker recently purchased an ownership share in a company developing on-board hydrogen tanks for 10,000 psi working pressure, suggesting that this may become a serious option for reducing on-board hydrogen storage volume (or adding range) if the compression energy and cost challenges can be overcome.

Conventional vehicle configurations may also eventually have to adjust to accommodate hydrogen's high storage volume without loss of payload space, but such unique designs would be costly in production. Early FCVs using compressed hydrogen are instead likely to provide a somewhat reduced range (although still several times greater than that of current electric vehicles) and payload space, which will reduce their marketability to an unknown degree.

On-board tank construction appears not to be a problem. Today, lightweight carbon fiber-wrapped cylinders are in use for CNG vehicles and have been demonstrated to provide exceptional crash safety under 5000 psi nominal working pressure. Burst pressures are reportedly beyond the 2.2 factor (i.e., >11,000 psi) typically required in pressure vessel codes. With volume production, costs and availability appear to be acceptable (i.e., under $1,000), although current prices, typically for single units or very small production runs, are in the $2,000 range. Safe refueling nozzle connection systems have been developed and work is underway to establish standards for refueling connections.

Another major disadvantage of compressed hydrogen for near-term commercialization is in its infrastructure capital and operating costs, as discussed elsewhere in this report. Apart from the substantial energy requirements of natural gas reforming or electrolysis, compression to 5000-6000 psi adds both compressor and energy costs. Despite these difficulties, all the technology required for compressed hydrogen generation and storage either exists or can be developed relatively quickly for early commercialization.

Liquid (Cryogenic) Hydrogen

Liquid hydrogen has an energy density three times higher than compressed hydrogen at 5000 psi, thereby theoretically resulting in major savings in volume. However, maintenance of its -253°F temperature requires extensive insulation. Liquid hydrogen's actual relative storage volume is driven by tank diameter (including insulation) which is in turn largely determined by insulation and vehicle packaging constraints. The result is very little storage volume advantage over CH_2 except with unusually large-diameter LH_2 tanks—that present their own vehicle design problems.

In addition, LH_2 production's far greater energy requirement results in correspondingly greater environmental impact. Most FCV developers are therefore not seriously considering on-board LH_2, although the delivery of cryogenic hydrogen to some early CH_2 compressor/fueling stations may be an expedient means of serving small numbers of fuel cell vehicles while the technology is being introduced. Some initial demonstration vehicles could also use LH_2 as a means of facilitating earlier introduction.

Research in the field of liquid hydrogen storage centers around the development of composite tank materials, resulting in lighter, stronger tanks, and improved methods for liquefying hydrogen.

Hydride Storage

Metal and chemical hydride storage of hydrogen are attractive for their potential to solve the storage space problem. However, they are as yet generally considered impractical due to their high weight (metal), cost (chemical), and high hydrogen release temperatures, causing slow startup and requiring complex thermal management. Hydride storage would therefore require a hybrid configuration using a battery for startup in addition to its other typical HDV functions.

Metal hydrides include a broad range of materials into which hydrogen can be driven under specific temperature and pressure conditions. The hydrogen becomes a part of the molecular structure, in effect producing a metallic alloy. This reaction is exothermic; to reverse it and release the hydrogen for use, the hydride compound is heated. The basic hydride material stays on-board the vehicle permanently. Its storage tank can be molded as needed to conform to vehicle geometry—a major advantage.

Chemical hydrides operate quite differently. The hydrogen-charged hydride is produced off-board and loaded onto the vehicle, rather than adding hydrogen to a material already stored permanently on-board. When it is discharged (e.g., through hydrolysis) in FCV use, the remaining chemical product must be removed from the vehicle to be recharged, and the recharging process may involve a major energy penalty. Despite these challenges, chemical hydrides are of interest for their potentially low weight and high hydrogen content. One advanced example, using sodium borohydride, may be reviewed at http://www.millenniumcell.com.

Hydrogen content by weight is still low in hydride development efforts. One metal hydride developer (Energy Conversion Devices, Inc.) has recently announced a prototype system storing hydrogen at a 7% density by weight, resulting in a major advantage in volume relative to compressed hydrogen. With the ECD system, storage of 6 kg of hydrogen would require 120 liters and weigh 120 kg (~260 lbs). However, this density still implies a fuel weight much higher than compressed hydrogen for the same range, resulting in a heavier and less energy efficient vehicle. Loading pressure and energy requirements are unknown. See http://www.ovonic.com/news/Sept13_2000.html for further details.

Despite the longer-term promise of such developments—and the corresponding *threat* of stranding investments in current compressed hydrogen technology—no practical hydride system appears likely to be ready for commercialization within this decade. However, this could change: Some automakers are working actively to improve hydride technology for FCV use. At least one has recently announced that its newest demonstration vehicle uses metal hydride storage, and another is involved in testing sodium borohydride storage and regeneration.

Other Methods in Development

Carbon nanotubes are microscopic tubes of carbon, two nanometers (billionths of a meter) across, that store hydrogen in microscopic pores on the tubes and within the tube structures. Similar to metal hydrides in their mechanism for storing and releasing hydrogen, the advantage of carbon nanotubes is the amount of hydrogen they are able to store—theoretically—from 4.2% to 65% of their own weight in hydrogen.

Carbon nanotubes and their hydrogen storage capacity are still in the early stages of research and development. Only microscopic amounts have been created in laboratories, and there is no expectation of commercial demonstration soon.

Glass Microspheres are extremely small hollow glass spheres that may eventually be used to safely store hydrogen. The glass spheres are warmed, increasing the permeability of their walls, and filled by being immersed in high-pressure hydrogen gas. The spheres are then cooled, locking the hydrogen inside the glass balls. A subsequent increase in temperature can then release the hydrogen trapped in the spheres. Microspheres, or "Buckyballs," have the potential to be safe, resist contamination, and contain hydrogen at a low pressure, increasing the margin of safety. This technology, like nanotubes, is in an early stage of development.

Conclusions on Hydrogen Storage Outlook

Based on these considerations it is most reasonable to expect that any early commercialization of hydrogen storage for FCVs will rely on compressed hydrogen, and that the required external compression equipment and pressurized on-board storage technology will be available as needed. Liquid hydrogen, although possible, is not a strong candidate, but hydride systems could still become a major market force within this decade and therefore constitute an important uncertainty in early compressed hydrogen adoption.

Appendix

H Refinery FCV Fuel Alternatives to Gasoline

Frank Biasca

SFA-Pacific, Inc.

Scale of the Problem

Based on a scenario of 100,000 in FCV sales and 175,000 in use, each accumulating an average of 12,000 miles per year at a fuel economy of 60 miles per gallon, about 2,300 bbl/day of a hydrocarbon feed to the on-board FC reformers would be required. The capacity of California's refineries is about 2,000,000 bbl/day of crude, producing about 1,000,000 bbl/day of gasoline. The FCV requirement is, therefore, about 0.115% of the crude intake or 0.23% of the gasoline production. Removing this small fraction would have little noticeable effect on blended gasoline quality or refinery operations. Rather, supplying it becomes the 'nuisance' logistics of separating, storing, and distributing a minor stream. This is not expected to add significantly to the cost.

A Promising Fuel Choice

Most refinery hydrogen is produced by steam reforming of natural gas, about 1,300 million scf/day in California. Hydrogen can be (and is) produced by steam reforming of heavier (higher molecular weight) feedstocks, at increasing complexity and cost as the molecular weight of the feedstock increases. The lightest and most attractive stream for on-board reformers, heavier than butanes, is a C5/C6 light straight run naphtha. California refineries have a capacity to isomerize (i.e., use) about 100,000 bbl/day of this stream.[1] <u>The fuel cell requirement would be about 2.3% of this capacity</u>. The product will be low in sulfur content.

In perspective, the energy supplied to the fuel cells is quite small when related to commercial production of hydrogen or methanol. The hydrogen supplied by steam reforming 2,300 bbl/day of C5/C6 would be about 30 million scf/day or about 30% of the 100 million scf/day capacity of a large new natural gas steam reforming hydrogen plant.

---

[1] Isomerization converts the C5/C6 stream to a much higher octane value blending stock. The stream is hydrotreated in the front end of the process to eliminate sulfur.

Similarly, the energy content of 2,300 bbl/day of C5/C6 is equal to that of about 550 ton/day of methanol, about 30% of the capacity of a current world-scale methanol plant. Spread over the output of all California refineries, this is a very small amount.

Longer-Term Fuel Supply Implications

The 40,000-vehicle sales milestone implies a sales-growth trajectory that could yield 350,000 vehicles within five more years. The fuel requirement at that point would be about 4,500 bbl/day, 0.45% of the total gasoline production or 4.5% of the California refineries' C5/C6 naphtha isomerization capacity. This is still a minor percentage of refinery production. Scaling up with continued FCV sales growth would continue to require only a small share of the C5/C6 capacity for another decade or more.

Existing Models for On-board Reformer Development

Steam reforming of naphtha to produce hydrogen is a well-developed process. Steam naphtha-reforming accounts for 13% of worldwide hydrogen capacity, mostly located in areas of low natural gas availability such as Japan, South Korea, and Europe. Steam naphtha reformers are more complex than steam methane reformers, and may require a fired feed vaporizer, a hydrodesulfurization reactor and a sulfur adsorber. The steam methane reformer requires only a sulfur guard bed. However, the point here is that this existing plant-scale process is a good starting point for the development of a fairly simple on-board reformer for the naphtha or C5/C6.

Similarly, there are several process vendors of C5/C6 light naphtha isomerization processes for octane enhancement. These processes include hydrogen treating and desulfurization, and could produce a suitable feed to a FC reformer.

Steam methane reformers which process feeds containing significant quantities of heavier components (e.g., propane, butane, pentanes, etc.) include a pre-reformer to convert these components to methane and CO_2 prior to feeding to the reforming section. During the period of low natural gas availability in the late-70s and early 80s, several 'rich gas' processes were used to convert naphtha to 'synthetic natural gas,' that is, to methane. These processes were reported to be able to handle feeds with boiling ranges of up to 420°F or 610°F and produce a gas suitable for steam methane reforming. SFA Pacific is not aware of any of these plants still operating today. Such a two-step process may not be practical for an FCV.

These considerations suggest that the C5/C6 stream is the most attractive candidate as a very low-sulfur and more easily reformed refinery-product alternative to gasoline for FCVs.

Appendix

I Methanol U.S. Gulf Price Forecast, 2001-2010

Jim Crocco

Crocco and Associates

Introduction and Background

The global methanol industry is undergoing a significant change in many ways. Beginning in the middle of this decade, larger and lower cost remotely located methanol production facilities are likely to effectively overwhelm and replace a large number of smaller and higher-cost Gulf-region and domestic plants. There will be some limited exceptions, but they will not prove to be important since they will be small and local in nature—not impacting global conditions in a significant way.

Until recently, methanol cash production costs in the U.S. Gulf (including feedstock, plant operating and general sales and administration/overhead, but not depreciation or debt repayment), had established the "floor" for global methanol pricing, plus a certain margin that changed with market conditions. Throughout history the U.S. has been the largest methanol consuming and producing country in the world. As such it greatly influenced world market prices. The U.S. methanol industry proved in the 1980's its elasticity and flexibility in its ability to adjust to negative production economics. As new and lower cost methanol production came on line around the world in the 1970's and early 1980's, many U.S. plants found that they could not compete with the larger off shore facilities that enjoyed longer term and lower natural and associated gas feedstock pricing. Some feedstocks were then and are today tied to methanol market prices, which included the feedstock supplier, usually a government, as a partner in the market risk.

Many U.S. methanol plants were sidelined, which eventually resulted in increasing world prices due to short-term supply shortfalls. But they were not "shut down" in the classic sense. When feedstock gas prices in the U.S. approached or went much above $2.00 per MMBtu on a temporary basis, many of these facilities became uneconomical. As long as feedstock prices in the U.S. Gulf remained below $2.00–2.50 per MMBtu on a sustained basis, most U.S. methanol production could favorably compete with off shore plants. At the time high natural gas values were not predicted for the long term and the plants were put on standby to be reactivated in the future when feedstock values declined to a level that once more provided U.S. Gulf methanol producers a margin of competitiveness. Eventually, natural gas prices in the U.S. fell to a relatively low sustained level wherein every one of the previously shut down plants was restarted for economical and competitive reasons. This lasted for more than ten years.

Factors in Current and Future Change

The global methanol industry is now entering into a somewhat similar situation as that of the early 1980's but at the same time it is drastically different in some important aspects. A major change is the new wave of lower cost offshore production that is being planned that will threaten not only U.S. Gulf methanol producers, but any others in the world that do not enjoy geographical and/or captive advantages. Unfortunately for the U.S. and higher cost methanol producers around the world, there are some other conditions that were not prevalent two decades ago that greatly threaten their existence today. These are leading to a new and lower price trend, as explained below.

Lower and more realistic offshore feedstock pricing of today

During the 1970's, when a number of new methanol plants were being planned for some more remote areas, practically every crude oil forecast predicted values and prices well above $50 per barrel. In fact, there were forecasts of $60–80 per barrel well into the 1990's. With alternative flared gas pricing at fixed levels between $0.50-$1.50 per MMBtu as a methanol feedstock, much below its crude oil equivalence, it was easy to assume at the time that methanol would force its way into various fuels outlets. These were to be stationary power generation and transportation fuels throughout the world.

Many methanol plants were constructed on this premise, although virtually nothing was done by methanol producers, either new or established, to promote these new fuels outlets. As is the case to this day, the methanol industry does little to protect or expand its future. This has been left to other industries or associations, such as car manufacturers, environmentalists, fuel cell developers, and others who require methanol. The methanol plants were built, crude oil drastically declined in price in the mid 1980's and the potential methanol fuels outlets, although attractive for environmental reasons, never materialized for economic reasons.

Methanol feedstock value ideas in remote regions have now changed drastically from that envisioned just one or two decades ago. An abundance of relatively cheap natural and associated gas is available for methanol production around the world. There is still a large quantity being flared. In fact, according to some estimates, about 40% of the flared gas from crude oil production in the world can be found in the country of Nigeria. At least two new world scale methanol plants, one in Norway and another in Equatorial Guinea, were built primarily to dispose of flared associated gas. This trend is continuing as resource producers, be they companies or governments, seek to "monetize" this otherwise wasted asset. Therefore, methanol feedstock values and prices in remote world regions are becoming more and more competitive and "fixed" on a long-term basis. Some are even tied to changing methanol market conditions and values at any given time.

This flexibility in feedstock values is something that U.S. Gulf methanol producers, and others located in consuming areas where there are better alternative values for feedstocks, do not enjoy, and this will result in the further rationalization of the global industry. Natural gas in these regions is considered as a fuel and not a petrochemical feedstock. In remote areas it is a stranded feedstock resource and not a fuel. There is concern that NGL's, LNG's, GTL's, MTO, etc., when developed, will draw heavily on global natural gas supplies. This is certainly a concern but there are vast amounts of gas in the world, especially in the Arabian Gulf (Qatar, for example) that could sustain this growth for many years to come.

Much larger and more economical plants built in remote areas

Thirty years go a middle line methanol plant had a capacity of 1,000 tons per day, or less, and was based on a high-pressure process. Starting in the 1970's, the low-pressure process, developed by ICI and eventually others, was commercialized and the average plant capacity rose to 2,000 tons per day. Today a normal capacity is in the range of 2,500 – 3,000 tons per day. There are current plans to construct plants of 5,000 tons per day and there are plants of 10,000 tons per day on the drawing board. This economy of scale goes a long way in reducing methanol production costs versus the smaller and older facilities located in consuming regions.

Better maintenance and longer-lasting catalysts that provide more "on line" time

The methanol-producing industry has become quite sophisticated over the years**.** Better control systems, improved maintenance practices and longer-lasting catalysts have also contributed to lowering overall production costs. Obviously, older facilities can also take advantage of some of these cost cutters.

Larger dedicated methanol tankers with much lower delivery costs

Thirty years ago a 3,000-ton parcel of methanol that moved in international commerce was considered large. As new off shore producers sought to supply distant markets the parcel sizes increased up to 10,000 tons or more. Eventually dedicated methanol tankers were constructed or converted, beginning in the 1980's, in sizes up to 35,000–45,000 dwt. Early in 2000 Methanex launched a dedicated methanol tanker of 102,000 dwt, capable of carrying about 90,000 tons of product. This vessel could end up being one of a kind until when methanol becomes a major fuel and is moved in a fashion similar to petroleum fuels. Such a large vessel has port and berth limitations and restrictions but it calls on fuel-type berths in major ports. Freight rate reductions of 40% or more are realized which substantially reduces the delivered cost of methanol to major consuming areas from remote producing locations.

The Coming Shakeout

For these reasons, offshore and more remote methanol producers, both current and future, will realize lower delivered costs and these producers will replace the current high cost ones as global market price setters. Even some of the smaller and older profit-motivated methanol plants in remote regions, for example some in Trinidad & Tobago, could be threatened by new, cheaper production. The lowest price is the one that applies to the highest cost producer whose product is still in demand. But as new and cheaper methanol replaces the older and more expensive production, this cost line will continue to decline. The major transition from the control of the higher cost producers to the lower is expected when the next wave of new methanol production comes on line by mid-decade. At that time the current wave of rationalization in the global methanol industry should be complete and the high cost producers will have almost completely disappeared. Some will continue to operate for unique reasons.

Experience has demonstrated that global methanol market prices have followed a certain margin or spread above U.S. Gulf cash production costs. In the more distant past, for example up to about 5–7 years ago, this spread had been around 25 – 50% above production costs. But it has been narrowing as the high cost producers lose leverage, and now stands at about 15–20% above. This margin will continue to decline in the future to the zero point and will go below that level further out, over the next five years or so. As U.S. Gulf methanol cash production costs start to lose significance as a global price setter, more traditional global methanol supply and demand patterns will begin to take charge for a few years in the middle of the study period. There will be quite a distance for prices to decline, to the low level of the market reaching the delivered cash production costs of off shore producers, but the global market now seems to have been consolidated into an oligopoly. One major company and the methanol production centers in Saudi Arabia/Bahrain and Trinidad & Tobago, and perhaps Venezuela as well, control two thirds or more of world merchant market demand. This means that a handful of experienced global methanol producers control the world market.

With such a consolidation it is expected that markets will remain quite stable, as will prices, despite some "normal" global operating or utilization rates. These producers will do whatever they can to keep market prices high and margins wide. At that point some primary methanol suppliers to specific major markets, for example Venezuela to the U.S. Gulf, will emerge as the new market price setters. But in the mid term methanol pricing is expected to succumb somewhat to supply and demand pressures and operating or utilization rates, and there will be a downward dip for a few years beginning around 2005. This will be the interim period after U.S. producers lose pricing control and before the offshore producers take complete charge. It should be noted that the delivered cost of a commodity should not necessarily be its selling price.

Methanol Price Forecast Derivation

In the U.S., feedstock gas prices represent the major portion of cash methanol production costs. This is even more important today when natural gas values in the U.S. Gulf recently exceeded $6.00 per MMBtu and actually approached $10. Relatively strong prices are also predicted for the foreseeable future. Therefore, a natural gas component must be included in any methanol price forecast. Several natural gas forecasts were reviewed for the U.S. Gulf and the following average was derived:

Natural Gas Price Forecast For The U.S. Gulf (US$/million Btu's)

2000	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*
3.95	4.30	3.65	3.52	3.55	3.65	3.75	3.85	3.97	4.09	4.20

This analysis, then, assumed a certain feedstock consumption per ton of methanol. Some of the older plants in North American consume up to 36 million Btu's per ton and perhaps more. But these facilities either have already shut down for economic reasons or soon will. Therefore, this review concentrated on the relatively newer and more efficient plants in the U.S. Gulf, such as Lyondell and Beaumont Methanol, whom we assumed require 33.3 million Btu's per ton/110,000 per gallon as a higher heating value basis of feedstock.

Costs of plant operation and general sales and administration/overhead (GS&A/O) must also be included. These vary widely from plant to plant and company to company, but, when compared to the feedstock are not a major portion of total cash production costs. This review assumed the following operating and GS&A/O charges for a fairly efficient methanol plant in the U.S. Gulf that operates off natural gas and has a rated capacity of 700,000 metric tons per year:

Methanol Plant Operating And GS&A/O Costs: U.S. Gulf Example

Cost item	*U.S. cents/gallon*	*U.S. $/ metric ton*
Maintenance	3.25	$10.82
Insurance/other	0.75	2.50
Taxes	1.00	3.33
Labor	1.20	4.00
Utilities/electric/water/etc.	1.50	5.00
Gen. sales & admin./overhead	3.00	10.00
TOTALS	10.70	$35.65

There could be endless discussions on the specifics of the above. But the importance is not in the details themselves: There will always be variances since no two plants experience the same cost factors or overhead charges. It is the total plant operating cost that is important and, as mentioned above, when considering the feedstock cost, these plant operating and GS&A/O costs are not very important in the total. Cost escalations have not been a primary factor in operating methanol plants. Throughout the years changing practices, better controls, longer living catalysts, etc., have increased production efficiency and stabilized operating costs. But a small escalation was included in the out years of 2005 – 2010.

Using the factors above the following cash methanol production costs were derived for the study period, and apply to a reasonably efficient producer located in the U.S. Gulf:

2001 – 2010 Methanol Cash Production Cost Forecast Basis, U.S. Gulf
(US cents per US gallon)

Cost Item	*2001*	*2002*	*2003*	*2004*	*2005*	*2007*	*2010*
Natural gas @33.3 MMBTU	47.3	40.2	38.7	39.1	40.2	42.4	46.2
Total plant operating/GS&A/O	10.7	10.7	10.7	10.7	10.8	11.1	11.8
TOTALS	**58.0**	**50.9**	**49.4**	**49.8**	**51.0**	**53.5**	**58.0**

This table establishes the basis for a methanol price forecast. However, this forecast is supported primarily by cash production cost in the U.S. Gulf, which is anticipated to be important, and declining in importance, only until about the year 2005. After that other and quite new or non-traditional factors will impact global methanol pricing. These will be newer lower cost producers, forecasted global methanol industry operating rates, and supply and demand trends, all combined with an expected oligopoly. Therefore, for the U.S. Gulf this analysis separated the price forecast into two sections to provide a more graphic illustration of the differences. The first table below represents a certain influence from U.S. producers, albeit declining, for the first five years of the study period, but including the year 2000. The second global methanol price forecast table represents the anticipated “new” influences on global methanol market prices.

2001 – 2005 Methanol Price Forecast
(US cents per US gallon – FOB U.S. Gulf)

2001	*2002*	*2003*	*2004*	*2005*
64.9/67.9	55.3/60.0	52.0/54.4	49.8/52.3	45.3/48.0

As mentioned above, the next table describes the U.S. Gulf methanol price forecast for the “out” years of 2006 through 2010. The factors behind this forecast are somewhat different from the closer years and represent a global methanol market that is expected to change in its makeup. This change will result in a different set of circumstances influencing market prices.

2006–2010 Methanol Price Forecast
(US cents per US gallon, FOB U.S. Gulf)

2006	*2007*	*2008*	*2009*	*2010*
44.4/47.4	43.2/46.8	45.3/49.5	47.4/52.3	49.8/55.3

There could, obviously, be excursions above and below the above methanol price forecast but it is assumed pricing will fall within the ranges most of the time. At the present time all methanol consumed in California is imported except, possibly, for a small plant in Colorado that is currently sidelined but could be campaign-run. Any methanol imported into California from off-shore sources should be subject to the above, or perhaps somewhat higher because there is currently only one methanol supplier to the state. Competition and alternate supply sources should stabilize prices. Should domestic U.S. methanol start to be supplied to California, delivered prices would depend heavily on the origin of that product. If it were from the U.S. Gulf, which is doubtful, about 10–15 cents per gallon should be added to the above.

Conclusions

The price forecast described above assumes that methanol and its future pricing will continue to act as a global commodity. Regardless of what world region surfaces as a future price setter, global prices will tend to follow each region in search of a common ground.

The forecasts assume no economic, transportation, energy, military or governmental "surprises" during the study period, but rather orderly conditions in all world markets. There will be occasional periods of abnormal pricing conditions resulting in temporary and short-term excursions above and below the above prices that cannot be forecasted.

As there is no historical basis to extrapolate the future factors concerning methanol costs that will be directed by a new group of producers (off shore), the actual direction of prices in the out years could be on a more pronounced decline. However, at the same time, in the years 2005–2010, additional methanol demand is expected to develop in substantial quantities for the fuel cell, sewage treatment, MTO, etc. Dedicated or "utility" methanol plants could be constructed to supply some of this demand, similar to the methanol-to-gasoline (MTG) plants in New Zealand over ten years ago. Since these are as yet unknown factors but definitely potential developing outlets of individually significant size, it is expected that supply will lag behind expanded demand and markets will be somewhat stable during the out years of the study period. This condition will, likewise, tend to stabilize global methanol prices by reducing competition in a "hot" market. Therefore, methanol prices are expected to increase somewhat during the last few years of the study period but not to extent that they will inhibit any new outlets. A significant factor will be the value at the time of traditional fuels and feeds, which are expected to be higher than that of today. This, in itself, will tend to push methanol prices up. As long as traditional and new methanol outlets provide sufficient economic interest to expand production, capacity will keep pace with demand. Economic and market conditions will always strive to meet this goal.

The above illustrates that, because of high feedstock gas prices in the U.S. for the first half of the study, domestic methanol producers will experience a certain amount of economical pain and the industry will be forced to rationalize further. At that time offshore producers will enjoy rather attractive margins. In mid decade the conditions will change as lower cost off shore producers start to take charge. But at this point the factors that affect world methanol prices will become more supply and demand oriented. Overall, because of the consolidation of the global methanol industry that began in the mid 1990's and is expected to last through the study period, the expectation is that there will be few occurrences of seriously depressed world methanol prices. This could occur but they will be short lived and not significant over the long term.

Appendix

J Glossary: Technical Acronyms and Units

Shannon Baxter

California Air Resources Board

A. CHEMICAL NAMES

BTX	benzene, toluene, and xylene
C5	pentane
C6	hexane
CH_2	Compressed hydrogen
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
GHG	greenhouse gas
H_2	hydrogen
H_2S	hydrogen sulfide
HC	Hydrocarbon
LH_2	liquid hydrogen
LNG	Liquid Natural Gas
LPG	Liquid Propane Gas
M100	pure methanol
M85	fuel with 85% methanol, 15% gasoline
MeOH	Methanol
MTBE	methyl tertiary butyl ether
N_2O	nitrous oxide
NG	natural gas
NGL	natural gas liquid
NMOG	non-methane organic gases
NO_X	oxide of nitrogen

B. PROPER NAMES

ANL	Argonne National Laboratory
CARB	California Air Resources Board (also known as CARB)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BATF	Bureau of Alcohol, Tobacco and Firearms
CA	State of California
CaFCP	California Fuel Cell Partnership
CEC	California Energy Commission
US DOE	U.S. Department of Energy
US DOT	U.S. Department of Transportation
DTI	Directed Technologies, Inc.
US EPA	U.S. Environmental Protection Agency
GM	General Motors Corporation
GREET	Argonne vehicle emissions simulation model
NECAR	DaimlerChrysler FCV designation
NREL	National Renewable Energy Laboratory
OPEC	Organization of Petroleum Exporting Countries
PNGV	Partnership for a New Generation of Vehicles
SCAQMD	South Coast Air Quality Management District
US	United States

C. VEHICLE CLASSIFICATIONS

AFV	Alternative fuel vehicle (general term)
DMFC	direct methanol fuel cell
DMFCV	direct methanol fueled fuel cell vehicle
EFCV	ethanol fueled fuel cell vehicle
EV	electric vehicle
FCV	fuel cell vehicle
FFV	flexible fuel vehicle
GFCV	gasoline-fueled fuel cell vehicle
HEV	hybrid electric vehicle
HFCV	hydrogen fueled, fuel cell vehicle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
MFCV	methanol fueled fuel cell vehicle
PZEV	Partial Zero Emission Vehicle (CARB classification)

SULEV	Super Ultra Low Emission Vehicle (CARB)
SUV	Sport Utility Vehicle
ZEV	Zero Emission Vehicle (CARB)

D. MISCELLANEOUS TECHNICAL ACRONYMS

ATR	Autothermal Reforming
CAFÉ	Corporate Average Fuel Economy
DFMA	Design for Manufacturing and Assembly (trademarked)
E85	Fuel with 85% ethanol, 15% gasoline
EER	energy efficiency ratio
FC	fuel cell
FE	fuel efficiency
FOB	free on board (with location, for price basis)
FUDS	Federal Urban Driving Simulation
GIS	geographic information systems
GPS	global positioning system
GTL	gas to liquids
HHV	higher heating value
LHV	lower heating value
LSR	light straight-run (with regard to naphtha)
MTG	methanol to gasoline
MTO	metropolitan transportation authority
NGO	Non-Governmental Organization
NPV	Net Present Value
OH	Overhead (functions and costs)
O&M	Operations and Maintenance
PCF	Positive Cash Flow
PEM	Polymer Electrolyte Membrane
R&D	Research and Development
RFG	reformulated gasoline
RVP	Reduced Vapor Pressure
SMR	Steam Methane Reformer
SR	Steam Reforming
TAC	Technical Advisory Committee

E. UNITS OF MEASUREMENT

bbl	barrels
Btu	British Thermal Units
C	Celsius
dwt	deadweight tons
F	Fahrenheit
g	gram
gal	gallon
gge	gallons of gasoline equivalent in Btu
hr	hour
K	x1000
Kg	kilogram
kJ	kilojoule
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
k$	$thousands
lb	pound
mg	milligram
mi	mile
MMBtu	millions of Btus
mpeg	miles per equivalent gallon
mpg	miles per gallon
mtoe	metric tonnes of oil equivalent
ppb	part per billion
ppm	part per million
psi	pounds per square inch
scf	standard cubic feet
tpd	tons per day
v%	volume percentage
v/yr	vehicles per year
W	watt
wt	weight
yr	year