**R&D – 11,065**

# HYDROGEN FUELING INFRASTRUCTURE ASSESSMENT

BRITTA K. GROSS
General Motors Corporation

IAN J. SUTHERLAND
General Motors Corporation

DR. HENK MOOIWEER
Shell Hydrogen

PUBLICATION
GM RESEARCH & DEVELOPMENT CENTER

11 DECEMBER 2007

GENERAL MOTORS CORPORATION
RESEARCH & DEVELOPMENT CENTER
30500 Mound Road ■ Box 9055 ■ Warren, Michigan 48090-9055

---

DECEMBER 2007 R&D – 11,065

---

# Hydrogen Fueling Infrastructure Assessment

Britta K. Gross
General Motors Corporation

Ian J. Sutherland
General Motors Corporation

Dr. Henk Mooiweer
Shell Hydrogen

---

**Synopsis or Abbreviated Abstract**

This report demonstrates that a hydrogen fueling infrastructure that could support volume deployment of fuel cell-electric vehicles can be commercially viable and that, in the long term, customers will not have to pay more per mile for hydrogen than they do for gasoline today. Supporting data is provided by key infrastructure stakeholders, including Shell, GE, and the U.S. Department of Energy.

Intended Audience (for Presentation to the National Hydrogen Association, Sacramento, CA, March 30, 2008)

---

# ABSTRACT

Achieving a sustainable automotive transportation system that has low impact on the environment is an important long-term goal of our industry. To reach this goal, GM is pursuing a combination of technologies that will most effectively displace petroleum, reduce $CO_2$ emissions, decrease criteria pollutants, and lead to energy diversity. This strategy, in the nearer term, begins with internal combustion engine and transmission improvements, the increased deployment of E85 flex-fuel vehicles, and a broad range of gasoline-electric hybrid technologies. While many of the longer-term technologies required to achieve sustainability are not yet practical, there is a broad and growing consensus that a sustainable future rests on electrically driven automobiles. As vehicle propulsion shifts to electric power, hydrogen and fuel cells will play an important role in supplying the needed power on board the vehicle.

This paper focuses on the hydrogen fueling infrastructure, mainly from a U.S. perspective. It presents an assessment of its viability, and it discusses the issues and opportunities surrounding its creation. Initial implementations may not provide all the benefits of the end game, but they can feed further learning, build confidence in the long-term vision, and create the necessary asset base for future growth. It is important to view the transition to a hydrogen economy as a deliberate and steady stream of progress, where hydrogen production pathways change over time and environmental benefits increase through technological advances and policy measures.

The key conclusions of our analysis are:

- There is a significant and growing body of evidence suggesting that, in the long term, customers will not have to pay more per mile for hydrogen than they do for gasoline today. Supporting data is provided by key infrastructure stakeholders, including Shell, GE, and the U.S. Department of Energy (DOE).

- A significant challenge during the transition period will be matching the scale and timing of fueling investment with actual hydrogen demand. A balance must be achieved between the minimum investment to meet initial demand versus the value of abundant fueling station availability in support of fuel cell-electric vehicle (FCEV) sales growth. Geographic concentration and coordinated vehicle/infrastructure rollout will be part of the solution, and the role that government plays will be crucial.

- Business models based on the traditional notion of a gasoline fueling network are not necessarily optimal. GM continues to explore alternative fueling infrastructure approaches that can address the low-volume transition period challenge and provide a kick-start to the infrastructure.

# TABLE OF CONTENTS

## 1. EXECUTIVE SUMMARY

Achieving a sustainable automotive transportation system that has low impact on the environment is an important long-term goal of the automotive industry. To reach this goal, GM is pursuing a combination of technologies that will most effectively displace petroleum, reduce $CO_2$ emissions, decrease criteria pollutants, and lead to energy diversity. This strategy, in the nearer term, begins with internal combustion engine and transmission improvements,  the increased deployment of E85 flex-fuel vehicles, and a broad range of gasoline-electric hybrid technologies. Longer term, no technology holds more potential to diversify energy sources "upstream" of the vehicle and eliminate vehicle emissions than electric propulsion. And when the electric power comes from a renewable source, the entire energy pathway is effectively greenhouse gas emissions free. Batteries and fuel cells are the leading options for providing electric power on board a vehicle. Batteries are charged directly using electricity, and fuel cells are powered with hydrogen fuel.  Like electricity, hydrogen can be produced from many different energy sources, and since hydrogen can be extracted from water using electricity, any renewable pathway to electricity is also a renewable pathway to hydrogen. In this way, hydrogen and electricity can be viewed as interchangeable and complementary.

Hydrogen is a valuable option because it can be made not only from water and electricity, but also derived from any hydrocarbon, such as biomass, natural gas, or coal. This ability to produce hydrogen from a broad portfolio of domestically available energy sources makes it a very attractive alternative in efforts to effectively address energy diversity. The fact that water, electricity, and natural gas are widely distributed across the country also means that every home and business has access to all the raw materials needed to produce hydrogen.

As battery and hydrogen fuel cell technologies advance, it becomes clearer that each technology is important to the success of the other. Each brings unique advantages to the vehicle – batteries offer lower energy operating cost (but long recharge times and low energy density that limits vehicle range).  Fuel cells and hydrogen storage provide greater vehicle range and shorter fueling times (but require a new fueling infrastructure). Taken together, batteries and hydrogen fuel cells can optimize the use of diverse energy sources in support of transportation needs. Hydrogen can store electricity from intermittent sources (e.g. wind), balance grid loads via production with off-peak power, and provide an effective means of energy transfer to the vehicle for onboard storage. Bottom line, GM believes that hydrogen will play a major role in any long-term scenario where clean energy, sustainability, and zero vehicle emissions are end-game criteria, but we have to be prepared to make the investments necessary to bring these technologies to market and address the hydrogen infrastructure challenge. The creation of the hydrogen infrastructure requires a concentrated effort; this paper will conclude that with a sustained commitment by government and key stakeholders, the task is doable.

According to numerous, independently verified studies performed by key infrastructure stakeholders, a hydrogen fueling infrastructure that supports volume deployment of fuel cell-electric vehicles (FCEVs) can be commercially viable. These analyses typically report hydrogen supply costs (untaxed) in the range of $4-6 per kilogram for production, distribution, and dispensing, utilizing today's known technologies.

Considering that the energy content of a kilogram (kg) of hydrogen is approximately equal to the energy content of a gallon of gasoline, and that fuel cells are typically twice as efficient as internal combustion engines, we can use the general rule that a kg of hydrogen can be twice the cost of a gallon of gasoline for equivalency on a cost-per-mile basis. This means, for example, that $3/gal retail gasoline is roughly equivalent to $6/kg hydrogen, which suggests that hydrogen in volume can be competitive with the retail price of gasoline, even including federal and state taxes. It is also reasonable to expect that technology improvements over the coming years will reduce costs and make hydrogen increasingly competitive with gasoline by the time FCEVs are ready for high-volume deployment. The DOE hydrogen cost target is $2-3/kg, and several pathways appear promising relative to this goal.

The results of the cross-industry/government analyses referenced in this paper are further substantiated by energy industry players' internal assessments and public statements. Shell asserts that hydrogen as a transportation fuel can be supplied synergistically with hydrogen produced for industrial use. The initial utilization of existing hydrogen production capacity (from large-scale natural gas reformers), supplemented with new, large-scale natural gas reforming facilities as increased capacity is needed, is a commercially viable path. GE has announced an electrolyzer concept that they say will produce hydrogen at $3/kg, or $1.50/gal gasoline equivalent (cost-per-mile basis, doesn't include the cost of delivery/dispensing). These different approaches both claim the potential for commercial viability at modest volume levels. And while the economics and volume potential of home/community fueling are uncertain, we know that Honda is on its third-generation system and may offer this option to early drivers of its next-generation FCEV.

Today, more than 40 billion kg of hydrogen are produced globally each year. This is enough hydrogen to fuel over 130 million FCEVs. More than 25 percent of this hydrogen (enough to fuel ~33 million FCEVs) is used by the oil industry in the processing of petroleum. In the U.S., roughly 7.5 billion kg of hydrogen is produced each year, mainly using natural gas as the feedstock. Because this large hydrogen industry already exists, the costs related to the production of hydrogen from natural gas are well understood. It costs about $1.20 to produce a kilogram of hydrogen, depending on the production scale (2002 analysis - captive plant gate cost - does not include delivery/storage/dispensing). In the near term, natural gas will continue to be the dominant feedstock for U.S. hydrogen production. For reference, an increase in U.S. natural gas consumption of about two percent would support sufficient hydrogen production to fuel ten million FCEVs, which implies sufficient lead time for the development of alternative feedstocks (e.g. clean coal, biomass) and production pathways to supplement natural gas-based steam methane reforming.

Shell's modeling work suggests early hydrogen production has the potential to be economically viable by heavily leveraging the existing asset base. According to Shell, hydrogen production plants are within reach of almost every major metropolitan area in the U.S. Existing surplus hydrogen capacity, along with surplus capacity of industrial hydrogen units that will be newly built, can supply adequate hydrogen for the early transportation market. The typical output of a new steam methane reforming (SMR) unit to produce hydrogen from natural gas is 120,000 kg/day, sufficient to fuel over 140,000 FCEVs.

A more significant hydrogen fueling challenge is downstream at the retail level. One key driver of hydrogen cost can be low utilization of the station-related capital investment. Our modeling work with Shell suggests that station utilization can be improved by:

- Focusing early vehicle deployment in select, concentrated geographic regions.

- Coordinating vehicle and station deployments.
- Aggregating, or consolidating, demand at each station.

From the infrastructure provider's perspective, it is important that there are just enough stations to ensure satisfactory utilization of each station, to keep the cost of hydrogen as low as possible. However, from an automaker's perspective, it is equally important that there are more than a sufficient number of stations so consumers perceive adequate fueling availability and a sufficiently large fueling coverage area. Government support can play a key role in balancing these conflicting criteria during the early hydrogen infrastructure growth period.

While the potential of hydrogen in the long term is fairly widely recognized, and strategies to reduce early market risk exposure have been identified, challenges remain in implementing hydrogen fueling infrastructure today. Difficulties are encountered in areas such as station siting and permitting, and there are no nationally accepted codes and standards. With experience over time, this situation will clearly improve. But while resolving these near-term challenges is necessary, it is not sufficient to generate the interest and investment to support volume development for hydrogen fuel cell-electric vehicles. Hydrogen providers will likely remain hesitant to move forward with the necessary investment unless two key enablers are in place:

- Strong (government) leadership and a clear national energy strategy that defines the specific role of hydrogen.
- Sustained long-term incentives for automakers, suppliers, infrastructure providers, and consumers to help overcome the near-term and long-term business risks associated with the high initial investment required until scale economies are reached for both the hydrogen infrastructure and FCEVs.

Today, the process of siting and permitting fueling stations is slow and unpredictable, consisting of a patchwork of local codes that vary greatly in interpretation. Liability concerns cause further delays in establishing stations. Government needs to help by:

- Increasing funding for technology development and validation efforts that lead to the development of appropriate codes and standards.
- Educating local officials relative to best permitting practices.
- Incentivizing state-wide consistency in local interpretation of codes.
- Offering a shared-liability solution to mitigate the financial risk to fueling infrastructure stakeholders.

California has been the most aggressive region in establishing a vision for hydrogen infrastructure and moving toward initial implementation. There are a total of 23 hydrogen fueling stations in operation in the state, with nine stations generally accessible in the Los Angeles area. An additional 14 stations are planned by energy providers, including Shell, Chevron, and BP. Though the vast majority of these stations are not retail-like, and none are commercially representative, they do signal an initial political will to advance the infrastructure in California.

Opponents of hydrogen often make arguments that can be true under certain circumstances but do not qualify as general conclusions. We list some of these arguments here and provide excerpts from our analysis in response. We have thought through these and many other complex issues around sustainable transportation and our confidence in the future of hydrogen remains high.

- Critics argue that while hydrogen vehicles may be clean-running, processes for producing hydrogen are not. For example, hydrogen from natural gas produces more emissions than producing gasoline from petroleum. This is true, but when emissions from the vehicle are factored in, overall “well-to-wheels” emissions are reduced. Critics also note that hydrogen produced via electrolysis is a “dirtier” pathway (i.e. higher $CO_2$ emissions) than gasoline. If the assumption is that the grid electricity is based on today’s U.S. average fuel mix (54 percent coal), then it is true that $CO_2$ emissions are higher for this pathway. However, there are options to produce green electricity as an energy source for green hydrogen. These options today come at a premium cost vs. coal-fired power plant electricity, but design improvements, scale economies, and internalization of environmental costs are expected to narrow the cost gap in the future, eventually making the transition to green electrolysis hydrogen economically attractive.

  On the other hand, if the technology and economics of emissions control and carbon sequestration in the stationary sector can be successfully addressed, coal could also play an important role in clean hydrogen production. In the end, sound judgment needs to be used when making decisions relative to where and how to produce hydrogen.

- Critics contend that an increased use of hydrogen will drive increased demand for natural gas and simply trade an oil import problem for a natural gas import problem. They further argue that diverting natural gas from the utility sector will result in an increase in coal usage (and, therefore, emissions) in electricity production. To address the concerns related to an increased reliance on natural gas, GM supports DOE’s strategy to promote a broad range of energy sources for hydrogen production. In addition, we carefully qualify that the use of natural gas is seen only as a way to kick-start the initial hydrogen transition period.

- Finally, there are many who argue that hydrogen is too dangerous. Since all fuels pose a potential hazard, the key question here is, “Is it more dangerous than gasoline?” The engineering approach applied to FCEVs and hydrogen infrastructure is based on gasoline precedents, so there is no reason to expect or accept anything less safe than we have today with gasoline. One inherent advantage of hydrogen is that higher tank-to-wheels efficiency means less potential energy stored on the vehicle for a given driving range. Nevertheless, more experience over time will be needed to increase comfort levels with a new fuel and a new fueling infrastructure. A starting point is hydrogen’s excellent industrial safety record achieved over decades at a global volume that has now reached over 40 billion kg per year.

Going forward, GM will continue to deliver a strong message of leadership commitment, confidence in the technology, and constancy of purpose. There is growing agreement that sustainable transportation depends on the electrification of the vehicle – by battery and by fuel cell. To ensure that major energy companies and governments continue to engage in the development of a hydrogen infrastructure and address the challenges this presents, GM will continue to be actively and visibly engaged.

## 2. TEN THINGS YOU SHOULD KNOW ABOUT A HYDROGEN FUELING INFRASTRUCTURE FOR AUTOMOBILES

1. Today, more than 40 billion kilograms of hydrogen are produced globally each year, enough hydrogen to fuel over 130 million fuel cell-electric vehicles [1][Appendix D-1].*
2. 53 percent of the hydrogen produced in the United States is used in oil refineries, enough to fuel 13 million fuel cell-electric vehicles [2][Appendix D-1].
3. A large hydrogen production site exists today near almost every major U.S. city [Fig 5-6].
4. Based on numerous studies, the near-term total cost of producing, distributing, and dispensing hydrogen for use in fuel cell-electric vehicles is generally in the $2.00 to $3.00 per gallon of gasoline range (cost-per-mile basis, does not include taxes) [Table 4-1][Table 4-2][Fig 4-1].
5. The U.S. Department of Energy (DOE) long-term target cost for producing, distributing, and dispensing hydrogen is equivalent to $1.00 to $1.50 per gallon of gasoline (cost-per-mile basis). Several pathways appear to have the potential to meet this target. [3]
6. A $10-15 billion investment, comparable to one-half the cost of the Alaskan pipeline in today's dollars, would establish a U.S. network of 12,000 hydrogen stations. These initial stations could fuel up to one million vehicles, and they would put hydrogen within two miles of 70 percent of the U.S. population (those living in the 100 largest cities). [Fig 5-1]
7. Natural gas, electricity, and water are widely distributed in the U.S., making virtually any location a potential site for hydrogen production (via natural gas reforming or water electrolysis) and vehicle fueling. Initial studies suggest "distributed" hydrogen production could be economically viable (cost equivalent to $1.55 per gallon or less, cost-per-mile basis) [Table 4-1].
8. To kick-start the fueling infrastructure, an increase in U.S. natural gas consumption of about two percent would support ten million fuel cell-electric vehicles and halve the $CO_2$ produced by an equal number of gasoline vehicles on a "well-to-wheels" basis [Appendix D-2][Fig 7-1]. Natural gas provides a well-understood and relatively low-cost source of hydrogen (production cost of approximately $0.60 per gallon of gasoline equivalent, cost-per-mile basis [4]).
9. Balancing infrastructure availability with fuel cell-electric vehicle sales growth and concentrating initial sales in specific geographic regions (e.g. Los Angeles) will be essential to manage early capitalization risk.
10. Bottom line: The hydrogen infrastructure for automobiles is economically viable and doable but requires a collective will by automakers, energy suppliers, and governments to overcome initial capitalization risks, motive early movers, and manage the transition.

**Fuel cell-electric vehicles generally can travel <u>twice</u> as far on a kilogram of hydrogen as internal-combustion-engine vehicles can travel on a gallon of gasoline.*

# 3. FINDINGS

1. While hydrogen is the most plentiful element in the universe, it does not exist in pure form on Earth. Instead, it is chemically bonded to other elements like oxygen in water and carbon in natural gas. To produce pure hydrogen, these chemical bonds must be broken, and this requires energy.

2. Like electricity, hydrogen is an “energy carrier” and can be produced using energy from diverse sources (fossil fuels, renewable sources, and nuclear power). As a result, hydrogen can enable energy diversity and reduce the automobile’s 96-percent dependence on petroleum [5].

3. Battery and hydrogen fuel cell technologies are highly complementary, and in any long-term scenario where clean energy, sustainability, and zero vehicle emissions are end-game criteria, both batteries and hydrogen will play a major role:

    - Each brings unique advantages to the vehicle – batteries offer lower energy operating cost (but long recharge times and very limited vehicle range), while hydrogen fuel cells provide greater vehicle range and shorter fueling times (but require a new fueling infrastructure).

    - Taken together, batteries and hydrogen fuel cells can enable broader use of renewable resources in transportation. Hydrogen can store electricity from intermittent sources (e.g. wind), balance grid loads using off-peak power, and provide an effective means of energy transfer to the vehicle for onboard storage.

4. Today, hydrogen is produced safely on a very large scale.

    - Worldwide, more than 40 billion kg are produced annually [1], enough to fuel over 130 million fuel cell electric vehicles [Appendix D-1]. This hydrogen is used primarily to produce ammonia (for fertilizer) and to refine oil [2].

    - 53 percent of the hydrogen produced in the U.S. is used in oil refineries, enough to fuel 13 million fuel cell-electric vehicles [2][Appendix D-1].

    - A large hydrogen production site exists today near almost every major U.S. city [Fig 5-6].

5. One kilogram of hydrogen has about the same energy content as one gallon of gasoline, and fuel cells are about twice as efficient as gasoline internal combustion engines. Therefore, fuel cell-electric vehicles can travel twice as far on a kilogram of hydrogen as internal-combustion-engine vehicles can travel on a gallon of gasoline. And, hydrogen can be competitive with gasoline on a cost-per-mile basis.

    - Hydrogen is produced from natural gas at about $1.20 per kilogram (2002 analysis - captive plant gate cost - distribution/dispensing not included) [4].

- The U.S. Department of Energy long-term target cost for hydrogen dispensed in a vehicle is $2-3 per kilogram (equivalent to $1.00-1.50 per gallon of gasoline, cost-per-mile basis). Several pathways appear to have the potential to meet this target and are being explored using DOE resources. [3]

- Based on numerous studies, the near-term total cost of producing, distributing, and dispensing hydrogen is $4-6 per kilogram (equivalent to $2.00-3.00 per gallon of gasoline, cost-per-mile basis):
  - DOE: $3.10-5.70 per kilogram from natural gas, wind, biomass, and coal gasification [Table 4-1].
  - IHIG*: $3.66-5.00 per kilogram from natural gas, coal, and biomass [Table 4-2].
  - Shell: $4.00-6.00 per kilogram from natural gas [Fig 4-1].

6. The biggest challenge in transitioning to a hydrogen infrastructure is managing the early capitalization risk. Geographic concentration and the balancing of infrastructure availability with fuel cell-electric vehicle sales growth will be essential.

7. A $10-15 billion investment would establish a national network of 12,000 hydrogen stations Fig 5-1]. (*Note:* The Alaskan pipeline cost $8 billion in the mid-1970s, equivalent to $25 billion in today's dollars.) This network would:

   - Fuel up to one million vehicles and put a hydrogen station within two miles of 70 percent of the U.S. population (those who live in the 100 largest cities).
   - Connect these cities with a station every 25 miles along the interstate highways.

   Concentrating in a single region and applying this same logic, greater Los Angeles would require about 240 stations (about $240 million).

8. Natural gas provides a well-understood and relatively low-cost source of hydrogen to kick-start the infrastructure. An increase in U.S. natural gas consumption of about two percent would support ten million fuel cell-electric vehicles and halve the $CO_2$ produced by an equal number of gasoline vehicles on a "well-to-wheels" basis [Appendix D-2][Fig 7-1].

9. Natural gas, electricity, and water are widely distributed in the U.S., making virtually any location a potential site for hydrogen production and vehicle fueling. Initial studies show some of these pathways could be economically viable:

   - GE claims to have an electrolyzer concept that could produce hydrogen (distribution/dispensing not included) at $3/kg, or $1.50/gal gasoline equivalent (cost-per-mile basis) [6].
   - DOE's modeling shows hydrogen from on-site natural gas reforming results in a cost of $3.10/kg ($1.55/gal gasoline equivalent, cost-per-mile basis) using current technology [Table 4-1].

- DOE's on-site electrolysis via wind scenario also projects hydrogen at $3.10/kg in 2015 [Table 4-1].

10. If motivation is the real issue, then sustained government support in the following areas is critical to ensure a successful transition to hydrogen and fuel cell vehicles:

    - Define the long-term role of hydrogen in transportation and support with consistent and compelling funding levels.

    - Provide early mover incentives for hydrogen suppliers as well as business risk mitigation support.

    - Fund the long-term, strategic development of a high-tech U.S. fuel cell industry capable of producing the world-class components required in polymer electrolyte, or proton exchange, membrane (PEM) fuel cells and hydrogen storage systems.

    - Provide incentives to OEMs and suppliers to reduce the significant early capitalization risk involved in the complex issues of commercialization and new technology deployment.

    - Fund government vehicle procurements and provide substantial early vehicle incentives to consumers.

    - Fund research on the most effective ways to safely, practically, conveniently, and cost-effectively store and dispense hydrogen (including advanced compressors and cryo-pumps).

    - Ensure that convenient and affordable hydrogen fueling is available to support OEM vehicle deployments.

    - Fund efforts that support the development of practical codes and standards to ease fueling station permitting and ensure high-quality hydrogen.

    - Bottom line, the infrastructure is doable but requires motivation to overcome the early capitalization risk. Government needs to ensure that infrastructure providers are sufficiently incentivized and motivated to put the necessary infrastructure in place.

**International Hydrogen Infrastructure Group, a consortium of auto, energy, and industrial gas companies that included Air Products, PraxAir, BOC, Shell, Chevron, BP, GM, DCX, and Ford.*

## 4. HYDROGEN INFRASTRUCTURE – COMMERCIAL VIABILITY

Over the past several years, GM has worked with a broad range of partners, including major energy companies such as Shell Hydrogen and industrial gas suppliers like Air Products, to analyze and assess the viability of a hydrogen fueling infrastructure. The results of these efforts and other independent analyses are largely consistent and provide strong evidence that hydrogen can be price-competitive with retail gasoline, with volume as a determining factor. Therefore, the infrastructure challenge is in working through the transition period until reasonable volume is achieved.

There are many opportunities, as we have learned in our modeling work with Shell, to mitigate this early transition challenge. In some infrastructure analyses, these considerations are not taken into account and results overstate hydrogen costs and the overall transition hurdle. For example, Shell asserts that a hydrogen plant would find multiple uses for its hydrogen during the early years of a transition when demand from the transportation sector would be relatively small, yet almost all other studies assume that a plant's entire production capacity is dedicated to transportation use. At low plant capacity factors, the economics would indeed be challenging, but no energy company would realistically operate in this fashion.

In analyzing and interpreting the results for the price of hydrogen, it is useful to keep in mind a simple rule-of-thumb that hydrogen is price-competitive with gasoline when a kg of hydrogen is twice the price of a gallon of gasoline. For example, at a gasoline price of $3/gal, hydrogen is roughly equivalent on a cost-per-mile-driven basis when its price is $6/kg. This is because the energy content in a gallon of gasoline is approximately the same as that in a kilogram of hydrogen, and a fuel cell is roughly twice as efficient as a gasoline internal combustion engine. Most studies assume that hydrogen is untaxed during the early years of the transition period.

### 4.1. DOE Infrastructure Modeling using H2A (Hydrogen Analysis) Model [3]

The most recent and comprehensive hydrogen infrastructure modeling work is DOE's H2A analysis effort. This model was developed over the course of the last several years with inputs from major energy players, particularly the industrial gas companies. Case studies using this model are summarized in Table 4-1 below.

Case study results based on this DOE modeling work conclude that onsite/distributed production of hydrogen via SMR (steam methane reforming of natural gas) is the least costly pathway and could already be competitive (untaxed) with the price of gasoline at approximately $1.55/gal (cost-per-mile basis), assuming a 1500 kg/day production capacity and a minimum 70 percent operating capacity factor. (The H2A model assumes a 10 percent internal rate of return on capital investment.) The key issue, therefore, is addressing the early market introduction period up to the point where station capacity is well utilized.

The analysis also suggests that there are several additional hydrogen pathways that are competitive with gasoline at roughly $2.50/gal (cost-per-mile basis), assuming currently available technology. These pathways are central biomass gasification and central coal gasification (with sequestration). Assuming continuing improvements in technology (i.e. cost reductions) over the next few years, these pathways would be expected to become increasingly competitive with gasoline by the time of fuel cell-electric vehicle commercialization.

Note that Shell's modeling work (described later) sees only a moderate role for on-site SMR.

- Low-cost hydrogen from on-site reforming still requires significant progress in reformer technology development.
- It is difficult to locate the relatively large on-site reforming equipment at retail sites.
- On-site reforming reduces the possibility of capturing and storing $CO_2$ from the many retail sites.

Although on-site SMR technology might play a role in early infrastructure roll-out or at remote station locations with large distribution distances from the nearest central hydrogen supply, Shell is convinced that central SMR is the most logical and least capital-intensive pathway – particularly when used in synergy with the production of hydrogen for industrial applications.

**Table 4-1. Summary of Case Studies based on H2A Model – Costs of Delivered Hydrogen** [3]
(Includes hydrogen production, delivery, and dispensing; untaxed;
10% internal rate of return on capital investment)

| H2 Pathway | Cost of Delivered Hydrogen ($/kg)* | | | Capacity | # FCEV fills/day | Operating Capacity Factor |
|---|---|---|---|---|---|---|
| | 2005 | 2015 | 2030 | | | |
| Distrib. – NG Reforming | 3.10 | 2.00 | | 1500 kg/d | ~300 | 70% |
| Distrib. – Wind/Grid ** | 5.70 | 3.10 | | 1500 kg/d | ~300 | 70% |
| Central – Wind *** | 9.50 | | 2.70 | 125,000 kg/d | ~25,000 | 41% (97% 2030) |
| Central – Biomass Gasification | 5.10 | | 2.40 | 155,000 kg/d | ~30,000 | 90% |
| Central – Coal Gasification (with Sequestration) | 5.10 | | 2.20 | 308,000 kg/d | ~60,000 | 90% |
| Central – Nuclear (Sulfur-Iodine) | | | 3.20 | 768,000 kg/d | ~150,000 | 90% |

*Divide delivered hydrogen costs by 2 for approximate gasoline equivalent pump price (untaxed)
**2005 – 30% wind / 70% grid; 2015 – 50% wind / 50% grid
***2005 – 100% wind; 2030 – 50% wind / 50% grid
*Note:* Results shown assume 350 bar dispensed; DOE verbal – 700 bar adds $0.10-0.20/kg

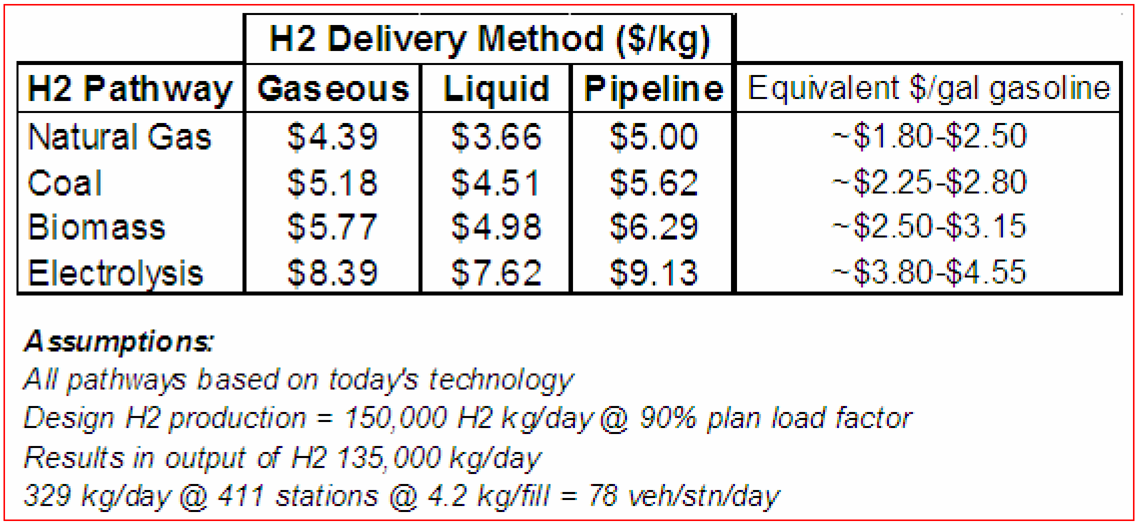
## 4.2. International Hydrogen Infrastructure Group (IHIG) Infrastructure Modeling [4]

GM participated directly in another industry infrastructure modeling effort within IHIG, a consortium of auto, energy, and industrial gas players that included Air Products, PraxAir, BOC, Shell, Chevron, BP, DCX, and Ford.

Results of this work, which assumed current technology, showed that natural gas reforming at a large, central plant resulted in the lowest hydrogen costs – and depending on the delivery mode, hydrogen was competitive with gasoline at roughly $2/gal (untaxed, cost-per-mile basis).

Similar to H2A-based results, these results suggest that hydrogen at large volume can be competitive with gasoline. The key issue, therefore, is the early market introduction period and the transition to high volume.

**Table 4-2. Summary of IHIG Results – Costs of Delivered Hydrogen** [4]
(Includes hydrogen production, delivery, and dispensing;
Untaxed; three delivery/distribution methods shown)



| | H2 Delivery Method ($/kg) | | | |
|---|---|---|---|---|
| **H2 Pathway** | **Gaseous** | **Liquid** | **Pipeline** | Equivalent $/gal gasoline |
| Natural Gas | $4.39 | $3.66 | $5.00 | ~$1.80-$2.50 |
| Coal | $5.18 | $4.51 | $5.62 | ~$2.25-$2.80 |
| Biomass | $5.77 | $4.98 | $6.29 | ~$2.50-$3.15 |
| Electrolysis | $8.39 | $7.62 | $9.13 | ~$3.80-$4.55 |

***Assumptions:***
*All pathways based on today's technology*
*Design H2 production = 150,000 H2 kg/day @ 90% plan load factor*
*Results in output of H2 135,000 kg/day*
*329 kg/day @ 411 stations @ 4.2 kg/fill = 78 veh/stn/day*

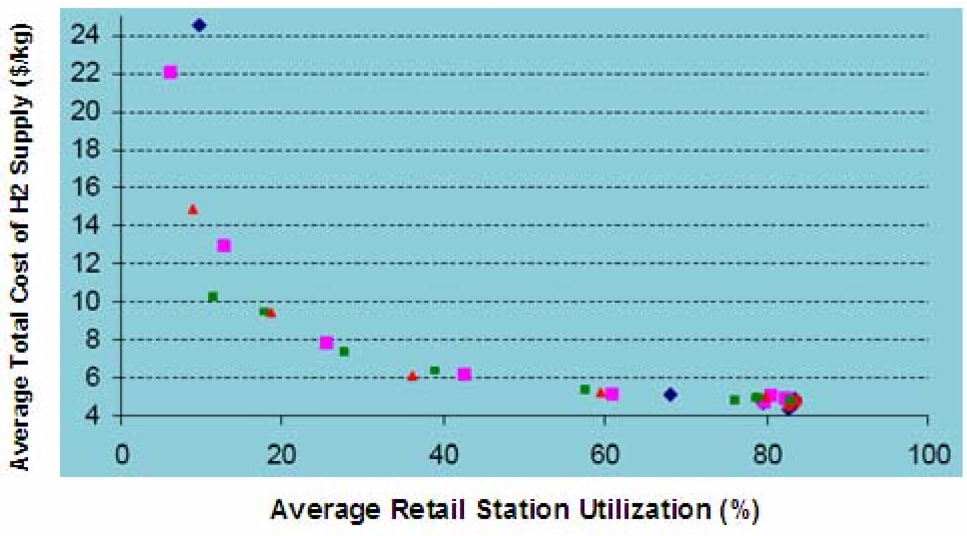
## 4.3. Shell Infrastructure Modeling

In a commercial study agreement, GM worked with Shell to assess the commercial viability of hydrogen in a specific geographic region – Los Angeles. For this study, Shell rigorously modeled the existing industrial hydrogen infrastructure in the region – hydrogen production at refineries, knowledge of merchant hydrogen availability, delivery distances, station footprints, etc. GM performed an in-depth conjoint market analysis that assessed fuel cell-electric vehicle demand relative to a variety of vehicle and infrastructure attributes. The goal was to determine, over time, how variation in various aspects of infrastructure buildup influences fuel cell-electric vehicle demand and *vice versa*. Some results of this study were shared early in 2006 at the National Hydrogen Association conference in Long Beach.

The joint GM/Shell modeling of the Los Angeles market concluded that large central SMR production, delivered initially via gaseous tube trailers and later via liquid tankers, is commercially viable at volume and results in a hydrogen cost competitive with gasoline.

Because Shell sees many opportunities for synergy with existing and new production infrastructure during the early transition years when there is lower hydrogen demand, the biggest cost challenge is downstream at the retail station. Station utilization heavily influences total hydrogen supply cost. As shown in Fig 4-1 below, aggregating vehicle demand at stations and closely coordinating vehicle deployment with infrastructure buildup to avoid overcapacity are key during the transition. The scenarios where high station utilization was reached sooner achieved lower total hydrogen supply costs much more quickly. A carefully coordinated approach to infrastructure buildup can meet overall vehicle hydrogen demand, avoid overcapacity, have minimal downside impact on vehicle sales, and lead to a significantly lower total cost of supply.

**Fig 4-1. Hydrogen Fuel Supply Cost as a Function of Station Utilization**



## 4.4. Other Energy Company Perspectives

Chevron is currently developing four different on-site reforming technologies (two natural gas-based, and two non-fossil feedstock-based) and demonstrating these at four separate fueling sites – clearly taking the lead among energy majors in the area of on-site reforming.

GE claims to have developed an electrolyzer that is capable of producing hydrogen for $3/kg (or $1.50/gal gasoline equivalent, cost-per-mile basis), assuming $0.05/kWh electricity cost (does not include cost of hydrogen delivery/dispensing). The electrolyzer achieves this cost-performance by replacing higher-cost tooled metal with a moldable, high-tech GE plastic called Noryl. This could improve the outlook for electrolysis and speed the transition to renewable energy-based hydrogen generation. This development is certainly worth following. [6]

**Fig 4-2. GE Electrolyzer – “$3/kg”**
(hydrogen production cost)

# 5. KEY ENABLERS

Since evidence suggests that a hydrogen infrastructure can be viable at volume, it is important to focus on enablers that support the early stages of infrastructure development. Among these enablers are:

- Deploying in concentrated geographic areas.
- Coordinating vehicle and infrastructure deployments.
- Aggregating demand at stations.
- Leveraging existing infrastructure.

These enablers are key to supporting a hydrogen infrastructure modeled after today's existing gasoline infrastructure – one that has evolved based on the traditional notion of a "corner gas station." But it is also worth considering non-traditional approaches to a fueling infrastructure, particularly during the early transition period when the challenges of a traditional infrastructure are greatest.

## 5.1. Deploying in Concentrated Geographic Areas

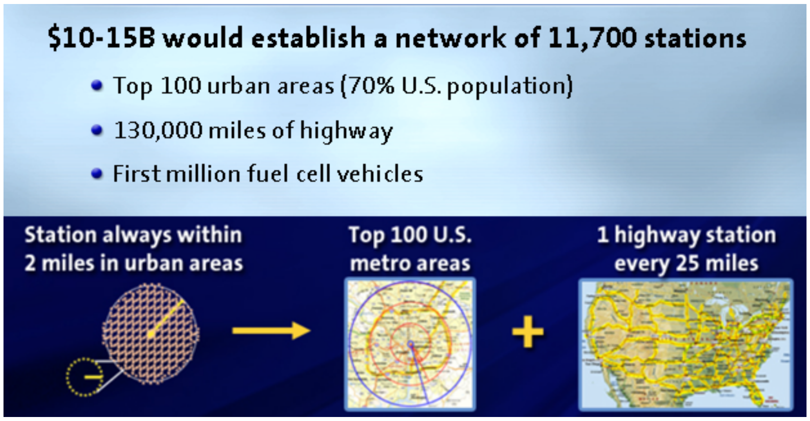
Broadly deploying fuel cell-electric vehicles and hydrogen infrastructure over a very large region will stretch the resources of a number of key stakeholders, among them:

- OEMs – Manpower and financial resources are required to support dealer and technician training, service parts infrastructure, advertising, public relations, and public outreach.
- Energy companies/hydrogen producers – Manpower and financial resources are required to support station installations, maintenance, and delivery logistics.
- Government institutions – Must provide financial incentives.

By concentrating all resources in a single (or a select few), largely urban, geographic area, it is possible to limit the financial exposure to both OEMs and the energy companies, yet still have a significant market in which to validate a large-scale deployment operation. Infrastructure learning can be achieved quickly and efficiently this way, with meaningful vehicle densities reached much sooner than if, for example, a nationwide or global deployment were attempted.

Take, for instance, the analysis we performed in 2003 to determine how much an initial nationwide "seeding" of fueling stations would cost. We concluded that it would cost $10-15 billion to build a network of 12,000 hydrogen stations. These initial stations could fuel up to one million vehicles, and they would put hydrogen within two miles of 70 percent of the U.S. population (those living in the 100 largest metropolitan areas). These stations would also cover all of the major highways and arteries connecting the largest U.S. metro areas with a hydrogen fueling station every 25 miles. By concentrating the deployment on a single region such as Los Angeles and applying this same logic, just 240 stations would be required (at a cost of about $240 million) – a significant reduction in complexity and cost.

**Fig 5-1. GM Analysis 2003**
(Feasibility of "seeding" a hydrogen infrastructure providing national fueling coverage)



**$10-15B would establish a network of 11,700 stations**

- Top 100 urban areas (70% U.S. population)
- 130,000 miles of highway
- First million fuel cell vehicles

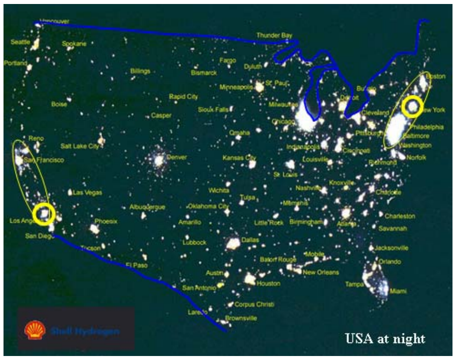
Station always within 2 miles in urban areas → Top 100 U.S. metro areas + 1 highway station every 25 miles

## 5.2. Coordinating Vehicle and Infrastructure Deployments

GM is currently targeting two key markets in the U.S. for fuel cell-electric vehicle deployments – Los Angeles and New York City. In Europe, we are targeting Berlin, while China activities are focused on Shanghai and Beijing. In the U.S. and Europe, Shell Hydrogen is pursuing a concept it refers to as Lighthouse Projects. The concept is to establish a mini-network of fueling stations around a hydrogen production plant that would support the fueling of a community of hundreds, and eventually thousands, of hydrogen vehicles. This coordination effort is another key enabler in efforts to lower hydrogen costs by ensuring that stations are built in areas where OEMs plan to deploy vehicles, thereby realizing good utilization of each station. Coordination is further needed to avoid overcapacity at both production sites and at the stations.

**Fig 5-2. Chevrolet Equinox FC Vehicle and Fueling Deployment Plan (U.S.)**

**Fig 5-3. Shell Lighthouse Project for Fueling**



In Europe, a very public coordination effort was announced in 2006 when a cross-industry group, including GM, BMW, DCX, Ford, Volkswagen, MAN, Shell, and Total, signed and released a joint position paper (Fig 5-4 below) related to future plans to coordinate the deployment of vehicles and hydrogen fueling stations in a single European location, namely Berlin. This paper demonstrates a concerted effort on the part of the industry participants to align thinking around deployment plans in order to concentrate resources to minimize financial exposure, and yet achieve all of the goals for the next demonstration phase.

Fig 5-4. **2006 European Position Paper Signed by Eight Key Stakeholders** [7]
(Goal: Coordinate the deployment of vehicles and hydrogen infrastructure)

Next Steps for the Development of a Hydrogen Infrastructure
for Road Transport in Europe

A common position paper of
BMW Group, DaimlerChrysler AG, Ford Motor Company, General Motors Europe AG,
MAN Nutzfahrzeuge AG, Shell Hydrogen B.V., Total France and Volkswagen AG

Despite these ongoing efforts to coordinate vehicle and hydrogen infrastructure deployments, it is clear that much work remains to ensure that sufficient hydrogen fueling is actually put in place and available in time to support the deployment of increasingly greater volumes of vehicles into the marketplace. Government must play a key role in providing this coordination and ensuring a successful outcome.

## 5.3. Aggregating Demand at Stations

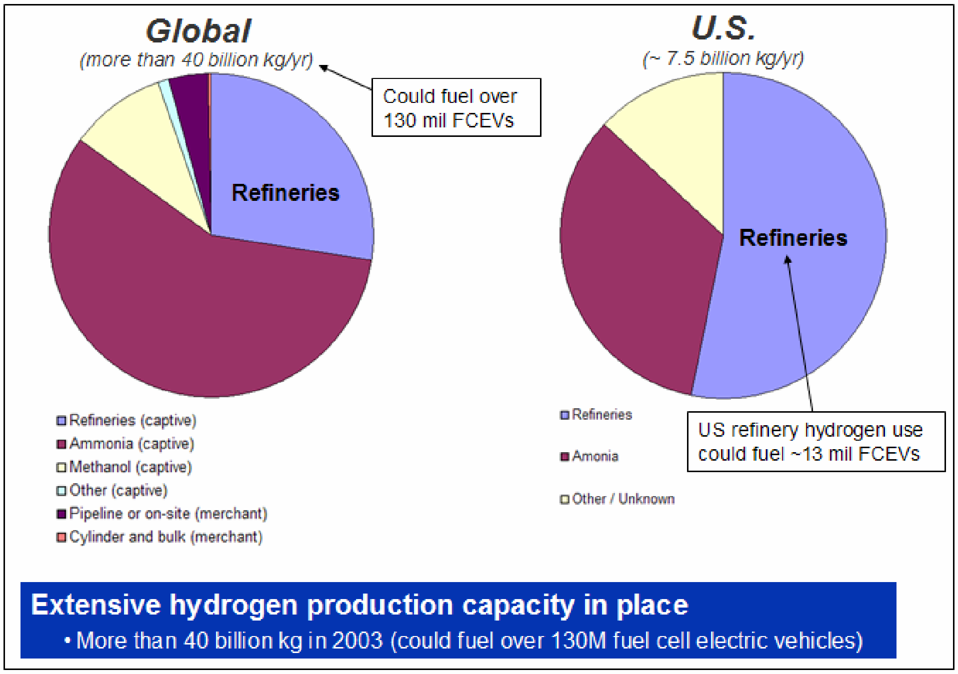
The most challenging costs on the infrastructure side are the downstream retail fueling stations. An underutilized station drives significant cost into the hydrogen price, so maximizing the use of each station is critical. By carefully coordinating the siting of fueling stations such that there are sufficient, but not excessive, numbers of stations, and by aggregating the vehicles to the maximum extent possible such that each station is highly utilized by a community of vehicles, the capital investment can be spread across a larger volume of hydrogen sales, and thus the cost per kilogram of hydrogen dispensed is reduced.

It is interesting to note that over the past decade there has been a significant decline in the number of gasoline fueling stations in the U.S. (a 13 percent reduction from 1995-2005 [5]) and a trend towards mega-fueling stations, e.g. WalMart. That is, the industry is already moving toward a revised model of fewer (in number), but larger (in size), fueling stations in a given geographic area.

## 5.4. Leveraging Existing Infrastructure

There is a large hydrogen industry today (globally, more than 40 billion kg/year).

**Fig 5-5. Global and U.S. Hydrogen Production Market (2003)** [1] [2]



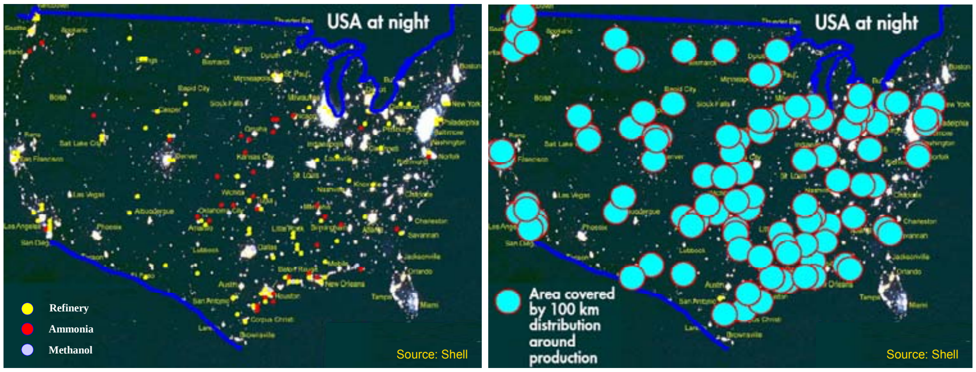
The primary uses of hydrogen in the U.S. are for oil refining and in ammonia production.

Hydrogen demand for oil refining is increasing, largely driven by:

- Increasing overall demand for gasoline.
- Increasingly stringent clean fuel regulations.
- Increasingly heavy, more sour crude supply.
- Decreasing demand for heavy fuel oils.

Hydrogen production sites are widely distributed across the U.S. and are often located near highly populated urban centers. In Fig 5-6 below, Shell demonstrates that hydrogen is already within reach of most large, urban areas in the U.S.

**Fig 5-6**. **Hydrogen Production Sites**



In certain areas there might be opportunities to leverage excess hydrogen manufacturing capacity that can be used during the early transition years to meet the lower levels of fuel demand before large investment in new production plants is needed. Clearly, the ability to minimize the cost of production is an important means of keeping costs low during the early years of the transition.

## 5.5. Non-Traditional Fueling Approaches

Up to this point, we have been describing a hydrogen fueling infrastructure that is essentially modeled to replicate today's traditional gasoline infrastructure, where consumers bring their vehicles to a station for fueling. But there are other ways to approach the early infrastructure – approaches that increase the general availability of fueling and minimize our reliance on external infrastructure providers. That is, if we leverage what we know about hydrogen storage and the technologies we have on the vehicle, such as OnStar and GPS, there may be ways to support our early FCEV deployments and limit, at least to some extent, our dependence on development of a fueling infrastructure on time that delivers the right performance and provides an adequate fueling coverage area.

Take, for instance, a scenario where a fleet of mobile fuelers <u>delivers</u> hydrogen to the vehicles. This approach could be used to kick-start the infrastructure in a new region until momentum builds and sufficient "permanent" infrastructure is installed. In this scenario, a small fleet of fuelers would travel throughout the coverage region and fuel vehicles based on a driver request, or based on our knowledge of the vehicle's location and tank level.

Both Linde and Air Products already offer 350-bar mobile fuelers with onboard storage (see Figs 5-7 and 5-8 below). However, these are not yet typically implemented as "mobile" fuelers – instead they are driven to a fixed location and the vehicles are brought for fueling.

**Fig 5-7. Linde Mobile Fueler**

Currently avalable in Europe today

Mobile and Autonomous LH2 & Compressed H2 Filling Unit.
1000 liter Liquid H2 Storag - High pressure buffer storage (450bar)
Compression. Cryogenic Compressor for 350 bar (5000 psig) filling
Fuel Dispensing. Liquid Hydrogen and Compressed hydrogen at 350 bar

**Fig 5-8. Air Products Mobile Fuelers**

Designs for high-pressure (700 bar) fuelers tend to be complex. Conceptually, however, these fuelers could be as straightforward as loading a trailer with a large number of tanks identical to those used on the vehicles and allowing the high-pressure gas to “cascade” into the vehicle tanks. Analysis is currently ongoing to understand the logistics (travel distances, fill rates, etc.) and fueling capacity of such an approach. However, early results suggest that:

- 10 fuelers at $2 million each = $20 million capital investment.
- Operating three shifts and each carrying roughly 100 kg of usable hydrogen could potentially support several thousand vehicle fuelings weekly.

A mobile fueling approach has the following additional features:

- 24-hour service, since both evening and daytime fuel deliveries have advantages. Evening fuel delivery has the advantage of longer park times for the vehicles; daytime fuel delivery has the advantage of higher concentrations of vehicles at some locations (e.g. parking lots of large employers).
- Leverages overcapacity of large stations – pipeline stations (those connected to large industrial hydrogen pipelines, such as in the Long Beach area of Los Angeles) and stations with on-site reformers tend to have larger amounts of hydrogen available. At low vehicle volumes, these stations are significantly underutilizing capital investment. A mobile fueler that fills there during off-peak periods (nearby station locations could very well be preferable to distant hydrogen production sites) improves the business case of both efforts.
- Launches the infrastructure in one large metro area and then has the portability to move on to the next large metro area. That is, once the metro area converts from a basically mobile infrastructure to an adequate network of permanent, large-capacity stations, then the mobile fuelers could move on to the next large metro area and kick-start its infrastructure, and so on…

The mobile fueling approach could also be very beneficial in attracting consumers by reducing the anxiety around real, or perceived, lack of fueling stations. Consumers would find the service more convenient and safer than traveling to “gas stations” to fuel.

There are, indeed, issues to be worked through in such an approach, such as the permits required (e.g. from U.S. DOT and local approving authorities) to move these fuelers through neighborhoods and parking lots, noise issues, privacy concerns, and even challenges surrounding the size of the mobile fueler required and its ability to maneuver through confined spaces. Nevertheless, a mobile fueling concept could be a relatively straightforward and self-reliant way to start up the infrastructure and attract the first early adopters.

Another non-traditional approach is the “energy station.” An energy station produces hydrogen either for vehicle fueling or for stationary fuel cells that produce electricity on site for local use or for the grid. Depending on the demands for fueling and/or power at any given time, the energy station has the flexibility to deliver what is needed. During the early transition years, when demand for vehicle fueling is low, the energy station can be used predominantly for power generation. Later, as vehicle volumes grow and the demand for fueling at the station increases, the energy station can scale up its hydrogen fueling capacity accordingly. This ability to adapt to evolving needs could have important economic advantages over a traditional infrastructure approach.

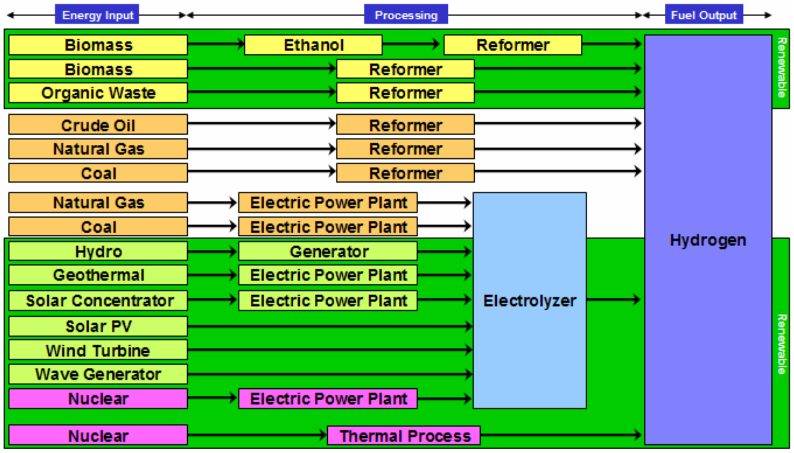
And while the economics and volume potential of home/community fueling are uncertain, we know that Honda is on its third-generation system and may offer this option to early drivers of its next-generation FCEV [8].

These and other non-traditional approaches warrant further investigation. They allow for planning and execution flexibility and could prove to be extremely useful in alleviating some of the risks inherent in the early transition period.

# 6. HYDROGEN PATHWAYS – WHERE WILL THE HYDROGEN COME FROM?

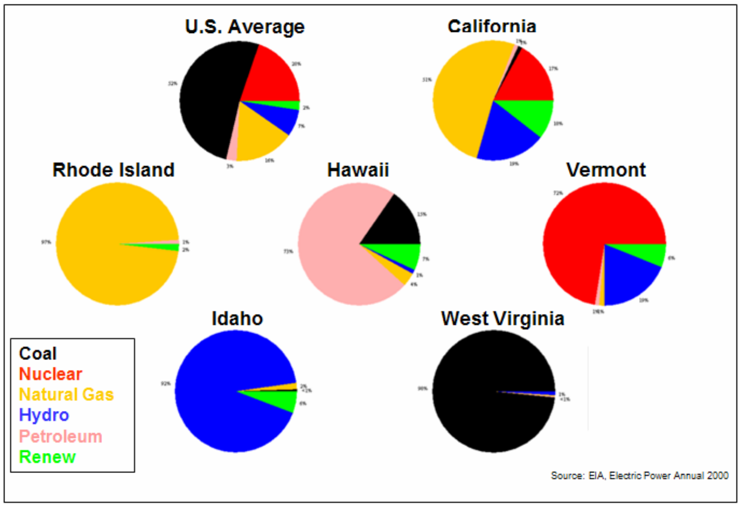
Clearly, there are strong drivers for migration to a wider portfolio of primary energy sources for transportation, rather than sole reliance on petroleum. Because hydrogen can be produced from a diverse portfolio of energy sources, many of them renewable, it offers tremendous potential as a fuel. Fig 6-1 below illustrates the breadth of potential hydrogen pathways, and Appendix A provides a description of the supply chains for hydrogen production pathways offering the greatest potential. A description of the gasoline supply chain is also included in Appendix B for reference and comparison.

**Fig 6-1. Hydrogen Production Pathways**



The best way to think about hydrogen is the same way we think about electricity. Most of us do not know what energy source is being used to power our homes – we only know that there are a variety of energy sources, including coal, natural gas, hydro, nuclear, and wind, all supplying power to the grid … so that when we flip the switch, the lights go on. Fig 6-2 below illustrates how diverse electricity generation is in the U.S.

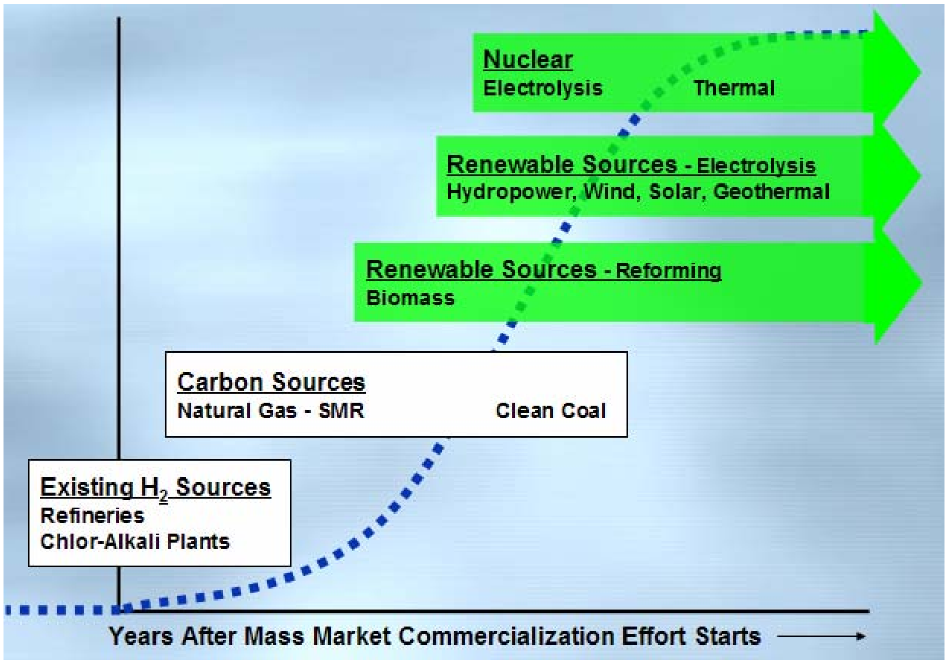
**Fig 6-2. U.S. Electricity Generation – Considerable Diversity** [9]



Source: EIA, Electric Power Annual 2000

As with electricity generation, there is no single best answer with respect to hydrogen production. There is a portfolio of options from which to choose. Each region will evaluate the resources it has available, and different pathways will become preferable in different locations at different times. In general, the sources of hydrogen will evolve over time as technologies that deliver more cost-effective solutions for cleaner hydrogen production are developed, and as public policies in favor of cleaner solutions are put in place. Fig 6-3 illustrates one way in which hydrogen production sources could shift over time.

**Fig 6-3. Sources of Hydrogen – Diverse and Evolving**

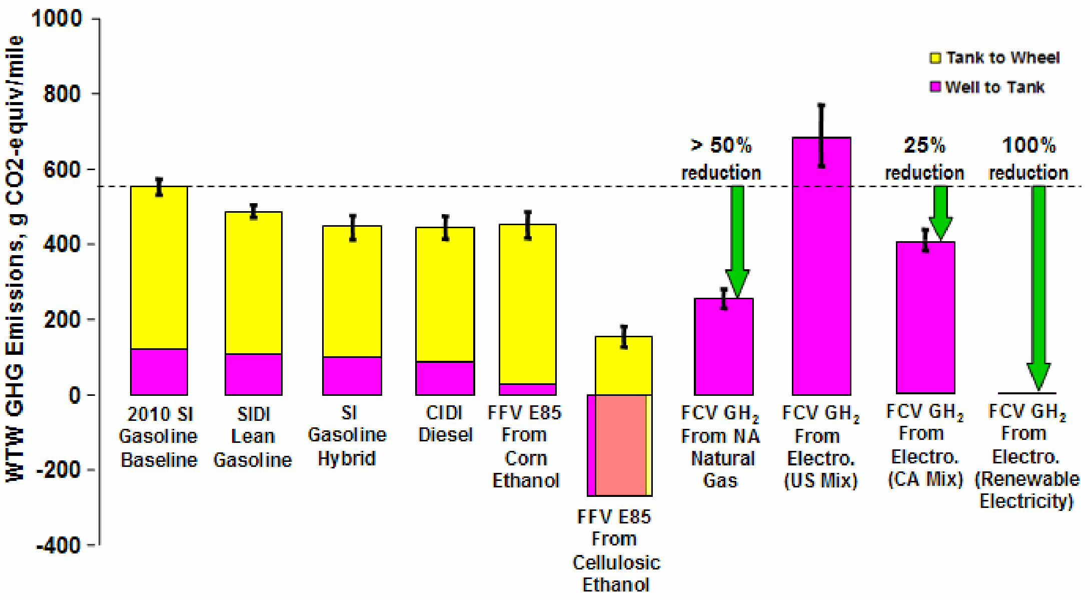


# 7. HYDROGEN PATHWAYS – WELL-TO-WHEELS ANALYSIS

Since a primary goal of a transition to hydrogen is sustainability, a key consideration in the pursuit of potential hydrogen production pathways is the overall emissions generated from the production, delivery, storage, and dispensing of hydrogen and its use in the vehicle, i.e. “well-to-wheels” (WTW) emissions. It is critical that we make sound judgments; in this regard, the GM/Argonne National Laboratory WTW study provides much insight into the emissions benefits of hydrogen as well as a few reminders that not every hydrogen production pathway reduces overall WTW emissions compared to gasoline [10]. Understanding this means we can make the right choices to pursue those pathways that lead to reduced emissions and eventual sustainability.

Fig 7-1 below, summarizing results from the study, shows GHG emissions for various vehicle propulsion technologies and fuel pathways. The most common method of producing hydrogen today (and the most likely leading into the hydrogen transition) is central SMR (steam methane – or natural gas – reforming). As shown, the overall GHG emissions for fuel cell-electric vehicles using SMR hydrogen are reduced more than 50 percent compared to the baseline gasoline internal combustion engine case.

**Fig 7-1. Well-to-Wheels Greenhouse Gas (GHG) Emissions** [10]



Natural gas reforming is currently the most cost-effective hydrogen production pathway, which explains why 95 percent of hydrogen produced in the U.S. is natural gas-based [11]. An increase in U.S. natural gas consumption of about two percent would support sufficient hydrogen production to fuel ten million FCEVs [Appendix D-2]. Clearly, a relatively small increase in natural gas consumption could meet vehicle fueling needs throughout the early transition years while technologies advance for more cost-effective alternative pathways.

Furthermore, wind, biomass and coal gasification are becoming increasingly competitive. (Solar costs have also dropped significantly but still need to decrease further before they are truly competitive with these other pathways.) Ultimately, the goal is hydrogen production based solely on renewable and greenhouse gas-neutral pathways.

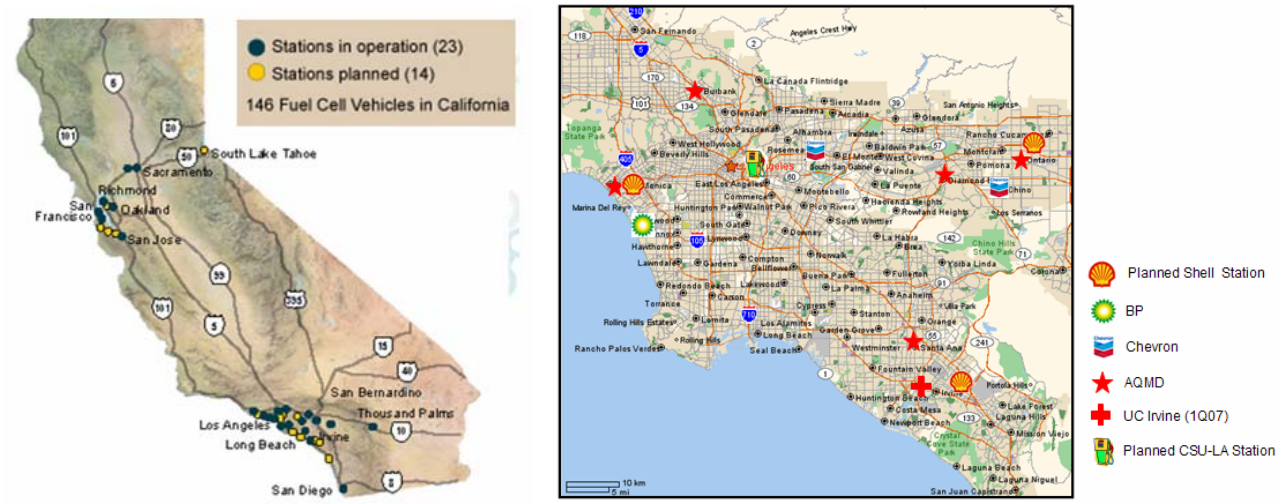
# 8. EXECUTION – WHERE ARE WE RELATIVE TO INFRASTRUCTURE TODAY?

The buildup of hydrogen fueling infrastructure is already happening in places like California, Berlin, and China.

## 8.1. California

There are currently 23 operational hydrogen fueling stations (including private fueling sites) in the state of California and an additional 14 are planned by the end of 2008 as part of the California Hydrogen Highway initiative. (In comparison, there is just one operational E85 station in California today, yet there are roughly 5 million flex-fuel vehicles on the road in the U.S.!) Granted, a large number of these hydrogen stations are on private and government property (e.g. city fleet yards), but it is clearly evident that a hydrogen fueling infrastructure is growing in California.

**Fig 8-1. California and Los Angeles Fueling Station Overview**



Los Angeles has the largest concentration of hydrogen fueling sites of any metropolitan area. There are currently nine operating hydrogen fueling stations in the greater LA area, as shown in the map at right in Fig 8-1 above. BP and Chevron have three stations; five of the stations are Air Quality Management District/municipal projects, and the other station is located at the University of California, Irvine. Shell plans additional stations in the area in 2007-2008, and a station at California State University-Los Angeles is also in the planning stages.

## 8.2. China

Efforts are also under way in China to install hydrogen infrastructure. Fig 8-2 below provides an overview of the existing and planned stations in Asia. Most efforts in China are clustered around Shanghai and Beijing. Because the population of China’s major cities is highly concentrated, and because there is relatively little intercity (city-to-city) driving, a hydrogen fueling infrastructure focused on the metropolitan area may provide adequate coverage and availability. An analysis of the number of hydrogen stations required to provide fueling within three kilometers of every point within the Shanghai and Beijing metro areas follows (see also Figs 8-3 and 8-4 below):

- Shanghai – 300 hydrogen stations would provide fueling coverage for the entire municipality of Shanghai (mainland), supporting over 450,000 FCEVs (note: population is ~20 million).
- Beijing - 150 hydrogen stations would provide coverage for the municipality of Beijing, supporting over 225,000 fuel cell vehicles (note: population ~14 million).

**Fig 8-2. Asia Fueling Station Overview** (*Source:* LBST)

**Fig 8-3. Shanghai Analysis – 3km to Stations**

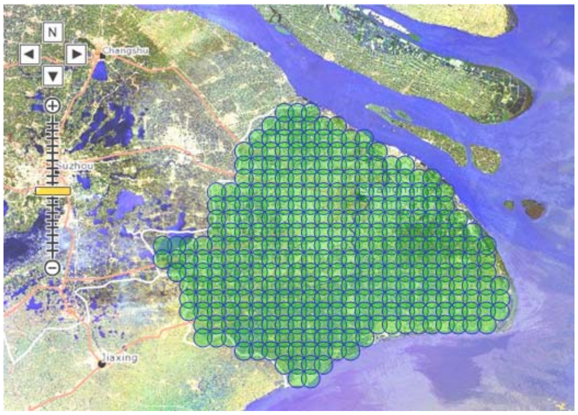
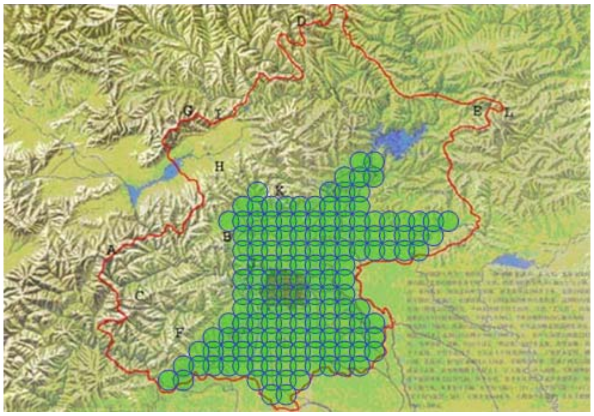


**Fig 8-4. Beijing Analysis – 3km to Stations**



China’s landscape is changing due to a rapidly growing economy and a rapidly increasing car parc, and the energy and environmental challenges associated with both. China has the potential to be an early player in the transition to hydrogen and FCEVs, particularly in the key metropolitan areas discussed here.

## 9. INFRASTRUCTURE: WHAT WILL IT TAKE?

There are a number of key areas where action on the part of government is needed to help address current issues with hydrogen fueling technology development and station installation. A more effective industry/government partnership would be useful in addressing these issues now, in order to speed the transition to commercialization when industry starts putting substantial resources at risk.

Among the most important actions that government must take:

- More aggressively fund the development of all the technologies required for the storage, compression, and fast-fill dispensing of hydrogen at fueling stations (e.g. high-pressure cryopumps, ionic compressors, cooling systems, infrared communication).
- Ease the fueling station/service site permitting process in selected communities. There is currently a patchwork of local codes with greatly varying interpretations, which cause the station permitting process to be unpredictable and extremely slow – typically 2-3 years.
  - Develop/support practical and easily implemented siting codes for stations and residential fuelers.
  - Ensure statewide consistency and local adherence to nationally developed codes and standards (e.g. NFPA, ICC).
  - Educate local officials (fire marshals, local government) regarding hydrogen safety and best permitting practices.
  - Support the permitting of publicly accessible, major branded fueling stations.
  - Support cycles of learning and a broad array of station options (e.g. overhead canopy storage, underground storage, on-site electrolysis or reformation, non-traditional fueling sites, 700 bar storage tanks).
  - Identify hydrogen-supportive communities, incentivize these communities, and proactively address NIMBY (“not in my backyard”) concerns.
  - Promote hydrogen as a safe fuel.
- Provide incentives, such as credits, loan guarantees, and tax incentives, to hydrogen infrastructure providers and station owners/operators to ensure that a minimum, convincing threshold of convenient fueling is available.
- Support/lead a practical, geographically concentrated, regional approach to station deployment.

See Appendix C for a more comprehensive list of the ways in which federal and state governments can provide additional support and incentives to develop a hydrogen infrastructure and promote the transition to FCEVs.

# 10. CONCLUSIONS

Numerous studies conclude that a hydrogen fueling infrastructure that supports the volume deployment of fuel cell-electric vehicles can be commercially viable. The challenge, therefore, is to put the right enablers in place, including sustained, long-term, and compelling government support and incentives, to ensure that the transition to high volume happens as quickly as possible.

High station utilization is critical to generating business justification for energy player engagement, as is geographic concentration, careful coordination of vehicle and fueling station deployments, and the leveraging of existing infrastructure. OEMs and energy companies are already aligning on targeted geographic areas (Los Angeles, New York City, Berlin, and Shanghai). Non-traditional approaches to hydrogen fueling could also be a very effective way to kick-start the infrastructure and lessen dependence on traditional infrastructure providers.

Continued expression of confidence is critical, and GM has taken a leadership position in this area. Energy companies and governments see GM active and visibly engaged in development of the hydrogen infrastructure to support our fuel cell-electric vehicle programs.

The key conclusions of our analysis are:

- There is a significant and growing body of evidence suggesting that, in the long term, customers will not have to pay more per mile for hydrogen than they do for gasoline today. Supporting data is provided by key infrastructure stakeholders, including Shell, GE, and the U.S. Department of Energy (DOE).

- A significant challenge during the transition period will be matching the scale and timing of fueling investment with actual hydrogen demand. A balance must be achieved between the minimum investment to meet initial low demand versus the value of abundant station availability in support of FCEV sales growth. Geographic concentration and coordinated vehicle/infrastructure rollout will be part of the solution, and the role that government plays will be crucial.

- Business models based on the traditional notion of a gasoline fueling network are not necessarily optimal. GM continues to explore alternative fueling infrastructure approaches that can address the low-volume transition period challenge and provide a kick-start to the infrastructure.

# APPENDIX A. HOW IS HYDROGEN MADE?

## A-1. Reformation and Gasification Pathways

- **Natural gas reforming** (or steam methane reforming, SMR) – Natural gas reacts with high-temperature steam (700-1000°C) under pressure (3-25bar) and in the presence of a catalyst, to produce hydrogen and carbon monoxide (along with a relatively small amount of carbon dioxide). The mixture is cooled (400-500°C) and, subsequently, the carbon monoxide and steam undergo a catalyzed reaction, the water-gas shift reaction, to form additional hydrogen and carbon dioxide. In a final process step, carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. The carbon dioxide can be sequestered at additional cost. The two-step process is represented by the reactions:

  ***Steam Methane Reforming Reaction***
  $CH_4 + H_2O\ (+\text{heat}) \rightarrow CO + 3H_2$

  ***Water-Gas Shift Reaction***
  $CO + H_2O \rightarrow CO_2 + H_2\ (+\text{ small amount of heat})$

- **Coal gasification** – Coal is converted into a gaseous mixture that includes hydrogen, by applying heat, pressure, steam, and a controlled amount of oxygen in a unit called a gasifier. The coal is chemically broken apart in the gasifier, setting into motion chemical reactions that produce a synthesis gas, or "syngas," a mixture of primarily hydrogen, carbon monoxide, and carbon dioxide. Adsorbers, or special membranes, separate the hydrogen from this gas stream. The carbon monoxide is reacted in a separate unit with water (water-gas shift reaction) to form carbon dioxide and more hydrogen. The carbon dioxide can be sequestered at additional cost. The gasification reaction can be represented by the (unbalanced) reaction:

  $CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$

  *Note: "Chemically, coal is a complex and highly variable substance. The carbon and hydrogen in coal may be represented in approximate manner as 0.8 atoms of hydrogen per atom of carbon in bituminous coal." (DOE ref)*

- **Biomass gasification** – Similar to coal gasification, biomass (plant-derived material) is converted into a gaseous mixture that includes hydrogen, by applying heat, pressure, steam, and a controlled amount of oxygen in a unit called a gasifier. The biomass is chemically broken apart in the gasifier to produce a synthesis gas, or "syngas," a mixture of primarily hydrogen, carbon monoxide, and carbon dioxide. The carbon monoxide is reacted with water to form carbon dioxide and more hydrogen. The carbon dioxide can be sequestered at additional cost. The gasification reaction can be represented by the (unbalanced) reaction:

  ***Simplified Example Reaction***
  $C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$

  *Note: "The above reaction uses glucose as a surrogate for cellulose. Actual biomass has highly variable composition and complexity, with cellulose as one major component." (DOE ref)*

## A-2. Electrolysis Pathways

An electrolyzer is used to split water into hydrogen and oxygen by applying an electric potential across an ionic membrane. Ions carry charge through the membrane, leaving hydrogen on one side and oxygen on the other. Electricity can come from any grid source, including the following renewable energy sources:

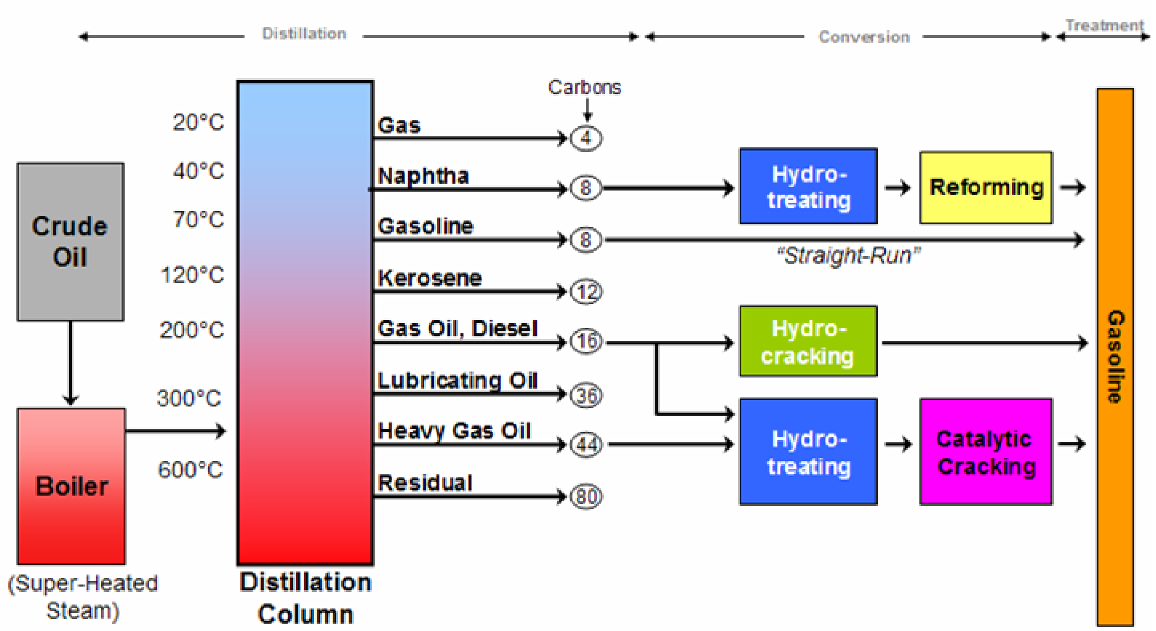
> **Wind** – Rotating turbine blades convert wind energy into electric energy by means of an electric generator.
>
> **Solar** – Sunlight striking a photovoltaic (PV) cell produces electricity. The PV cells may be in a fixed position, or they may be mounted to track the sun for optimal solar exposure. In an alternative approach, sunlight can be concentrated through reflectors, or lenses, to produce heat that boils water to drive a steam turbine, which powers a generator to make electricity.
>
> **Hydropower** – *Water at pressure is channeled through a pipe, or penstock, and then turns blades in a turbine. The turbine is coupled to a generator to produce electricity. In a run-of-the-river system, the force of the current applies the needed pressure, while in a storage system, water is accumulated in reservoirs created by dams, then released when the demand for electricity is high.*
>
> **Geothermal** – Steam and hot water are extracted from the earth and piped to a power plant. The steam, either directly or through flashing, is then run through a turbine to power a generator to make electricity. The condensed steam and remaining geothermal fluid are injected back into the hot rock to pick up more heat.
>
> **Nuclear –** The heat of a nuclear fission reaction is used to create steam. The steam is then run through a turbine to power a generator to make electricity. Alternatively, there is a direct nuclear-to-hydrogen pathway currently under development. In this pathway, water is put into a reactor and heated to very high temperature. A set of thermally driven chemical reactions occurs to split the water into hydrogen and oxygen.

## APPENDIX B. HOW IS GASOLINE MADE?

Originally, gasoline was produced almost exclusively through the simple distillation of crude oil, without any chemical conversion processes. Once motor vehicle use became more prevalent in the early 20th century, this "straight-run" gasoline could no longer meet vehicle fuel demand, and petroleum refineries have since developed several different processes to increase production. Today, there are three main processes common to all refining operations:

1. Distillation – The separation of crude oil into multiple chemical components.
2. Conversion – The breakdown of these components or fractions into various streams which will become finished products.
3. Treatment – The blending and purifying of the streams.

**Fig B1. Primary Pathways to Gasoline**



**Distillation** (separation), the first step in the petroleum-refining process, begins by heating up crude oil and then discharging the resulting vapors and liquids into distillation towers. Inside the distillation column, liquids and vapors separate into fractions based upon their density and boiling point. Liquid petroleum gas and gasoline, the lighter-weight components, vaporize and rise to the top of the tower where they condense back to liquids. The mid-weight liquids, such as kerosene and diesel oil, remain in the middle of the column, while gas oils, which are heavier fractions, remain a bit lower in the tower. The tar-like fractions with the highest boiling points settle at the bottom.

**Conversion** is the process of transforming the distillation fractions into multiple streams, most often through either cracking or reforming.

- Cracking is the most commonly used conversion method. Using extreme heat, the heavy hydrocarbons are broken down or "cracked" into lower boiling point hydrocarbon molecules. This *thermal cracking* process produces high-sulfur, high-nitrogen products which must be refined to meet gasoline standards. Cracking units consist of one or more tall, thick-walled, vessels or reactors in combination with furnaces and heat exchangers. *Catalytic cracking* supplements the heat with a catalyst to speed up the chemical reaction. Fluid catalytic cracking involves fluidizing the catalyst in order to continuously cycle it through the reactants; it is the foundational gasoline-making process in most modern refineries. *Hydrocracking*, while similar to catalytic cracking, adds hydrogen at higher pressures and lower temperatures to break down hydrocarbons. Hydrocracking can be used where catalytic cracking fails. While some refineries do employ hydrocracking to produce gasoline, it is more often used to produce diesel fuel.

- Reforming also uses catalysts as well as heat and moderate pressure to reform naphthenes and paraffins into higher-octane gasoline components.

- Hydrotreating typically precedes both catalytic cracking and reforming. This process uses hydrogen (hydrogenation) and a catalyst to remove about 90 percent of a wide variety of contaminants such as nitrogen, sulfur, oxygen, and metals from liquid petroleum fractions. These contaminants, if not removed from the fractions, can have harmful effects on the equipment, the catalysts, and the quality of the finished product.

**Treatment** is the final step prior to the actual delivery of gasoline to local gas stations. Since no single stream meets all the requirements of today’s gasoline, a modern refinery process must include blending and purifying. Variables such as octane level, vapor pressure ratings, and the environment in which the gasoline will be expected to perform are all considerations in this process. Refineries now use computerized blending programs to ensure all regulatory, economic, inventory, and performance requirements are met. Additives are the final part of the process needed to convert the streams into a finished gasoline product that meets government standards and certain specifications.

*References:*

http://www.chevron.com/products/prodserv/fuels/bulletin/motorgas/3_refining-testing/pg2.asp

http://encarta.msn.com/encyclopedia_761559518/gasoline.html

http://www.atsdr.cdc.gov/toxprofiles/tp72-c4.pdf

http://www.sjgs.com/refinery.html

http://www.chevron.com/products/learning_center/refinery

# APPENDIX C. ROLE OF GOVERNMENT

## C-1. Role of the U.S. Federal Government

**Overall:** The speed at which FCEVs penetrate the market depends heavily on a number of critical factors, largely beyond the control of any auto manufacturer. Among these is convincing the public that fuel cell and hydrogen storage technologies are safe and that fueling will be available. Another is convincing industry (auto, energy, supplier companies) that this initiative – unlike all other previous alternative fuel/vehicle programs – is truly a key U.S. priority, and that the transition will be accompanied by long-term, sustained government incentives, since the transition to a significant, meaningful volume of vehicles in the marketplace will indeed take some time. (The normal insertion of any automotive technology into the entire light-duty vehicle fleet takes more than 20 years!) Due to the technologies involved and the new supply base required, it will take from 500,000 to one million vehicle sales per year for an automaker to reach efficient scale. This represents a very significant capitalization risk to automotive OEMs and a very long-term prospect. As a result, the longer it is expected to take to reach these volumes, the more difficult it becomes to justify the initial investment required. Government incentives will be crucial to closing this gap.

Actions the government can take to enable the transition:

- Demonstrate unprecedented support of an alternative fuel program – articulate a clear and bold vision of a hydrogen and fuel cell transportation future.
  - “Moonshot” with advertising and public service campaigns.
  - Instill public confidence in the safety and benefits of hydrogen fuel through education.
  - Guarantee a total package of sustained, long-term, compelling incentives.
- Ensure a significant portion of government R&D resources/programs are allocated to research that will assist in addressing critical societal needs.
- Increase funding for basic and pre-competitive research, including breakthrough research that is generally high risk and high payoff. For example, there is a whole list of “substitution” materials that would reduce the cost of fuel cell propulsion systems, including low-cost, non-noble-metal, high-activity fuel cell catalysts; low-cost membranes; low-cost hydrogen-tolerant materials to replace stainless steel; and low-cost, high-strength composite fibers. DOE, NSF, and other research funds should be directed toward such high-risk, high-payoff endeavors.
- Fund government scientific research (U.S. national laboratories) on the most effective ways to safely, practically, conveniently, and cost-effectively store and dispense hydrogen at local fueling stations (e.g. compression/cryopump technologies, setbacks, footprint, composite storage materials, overhead canopy storage, underground storage, on-site electrolysis or reformation, non-traditional fueling sites), along with the requisite translation of that science into workable codes that can be implemented across the U.S. in a uniform way.

- Financially support the long-term, strategic development of a high-tech U.S. fuel cell industry capable of producing the world-class components required in PEM fuel cells and hydrogen storage systems.

- Increase funding of OEM development activities (i.e. demonstrations) and expand eligible expenses (e.g. in-kind).

- Provide incentives to OEMs/suppliers to reduce the significant early capitalization risk involved in the complex issues of commercialization and new technology deployment, including:
  - Manufacturing/assembly plant investment.
  - Dealer education, training, and salesperson incentives.
  - Service technician training and establishment of service parts inventories.
  - Building a new supply base/supply industry (e.g. for storage tanks, fuel cell components, and control systems) via loan guarantees, tax-free facilities, etc.
  - Product education and consumer outreach.

Focusing and mobilizing the necessary financial resources to underwrite such a massive transformation is becoming progressively more important. The question is, how as a country do we get this done? How do we work our way through the phase during which both the vehicles and hydrogen are too expensive because we are not at high-volume deployment? This is a business question for automakers. It is a tax and incentives question for governments around the world. Our ability to simultaneously develop answers to these questions from both a business and government perspective may well determine whether this technology can make it out of the lab and into the hands of consumers in a timely and efficient fashion, and whether the U.S. is placed in a competitively advantaged or disadvantaged position.

- Provide substantial early vehicle purchase incentives.
  - Utilize government procurement (fully funded) to stimulate early market demand that will help accelerate the achievement of efficient production levels and economies of scale.
  - Provide incentives for commercial fleets AND individual consumers (critical for mass market acceptance).
    - Could require $500 million per year or more during critical transition period.
    - Ensure fleet mandates/requirements are matched with the corresponding funds to cover the incremental costs to purchase and operate the vehicles. Mandates without the corresponding enabling incentives that stimulate changes in purchasing behavior are crippling to industry (OEMs as well as a very vulnerable supply base).
    - Provide compelling non-financial incentives to consumers (e.g. HOV lanes, parking privileges, tax advantages, etc.)

*Note:* Ensure that incentives are tied to vehicle volumes, not a timeline/date, and can adapt to changes over time – e.g. unanticipated increases in regulations can cause vehicle costs to increase over time.

- Ensure hydrogen fueling will be available, convenient, and affordable on a timetable that is complementary with the vehicles.
  - Promote advanced technologies that address critical societal needs, e.g. low-carbon hydrogen production.
  - Provide incentives to hydrogen infrastructure providers, station owners/operators (credits, loan guarantees, and tax incentives) to ensure a minimum, convincing threshold of convenient fueling is available.
  - Provide hydrogen incentives to ensure a compelling price relative to gasoline – e.g. no hydrogen fuel tax until some percentage of market penetration is achieved (recommend 10 percent), plus additional incentives (since the price of the fuel will be a significant motivator of hydrogen FCEV sales).

- Establish uniform codes and standards to ease fueling station permitting and ensure high-quality hydrogen.
  - It is currently very difficult to open stations in a timely fashion because codes are local and interpretations vary greatly. National standards would be very useful in order to expedite a rapid rollout once the U.S. decides to move to a hydrogen-based transportation system.
  - Create hydrogen safety and permitting “best practices” and educational materials for use with key stakeholders (e.g. emergency responders and permitting officials) at the state and local levels.
  - Government-approved uniform codes and processes for ensuring the quality of the hydrogen delivered to vehicles would be helpful. This is not as important initially when large energy companies are the likely source, but becomes critical as hydrogen sources diversify and entrepreneurs and small businesses enter the “fuels” business.

- Establish supportive hydrogen policies.

  At present, renewably sourced hydrogen production is almost always more expensive than hydrogen from natural gas (SMR). Since a truly compelling hydrogen price to consumers is one of the surest ways to drive FCEV demand, the higher costs relative to renewable hydrogen should not be passed on to consumers. There are 2 options:
  - Apply incentives broadly to all hydrogen feedstocks initially, including in particular natural gas.
  - Or require that all renewable portfolio standards (RPS) must be met with corresponding incentives for renewable pathways so that there is no cost-penalty with respect to the cost-effective production of hydrogen from natural gas.

- Build consumer enthusiasm for hydrogen and fuel cell-electric vehicles.

## C-2. Role of State and Local Governments

- Supplier industry development – financially support early supply base capitalization with loan guarantees, saleable emission credits, tax-free facilities.

- Provide substantial early vehicle purchase incentives for state/municipal fleets, commercial fleets, and individuals (critical to mass acceptance); other compelling, non-financial incentives (HOV lanes, parking privileges). Mandates without the corresponding enabling incentives that stimulate changes in consumer purchasing behavior are crippling to industry (OEMs as well as a very vulnerable supply base).

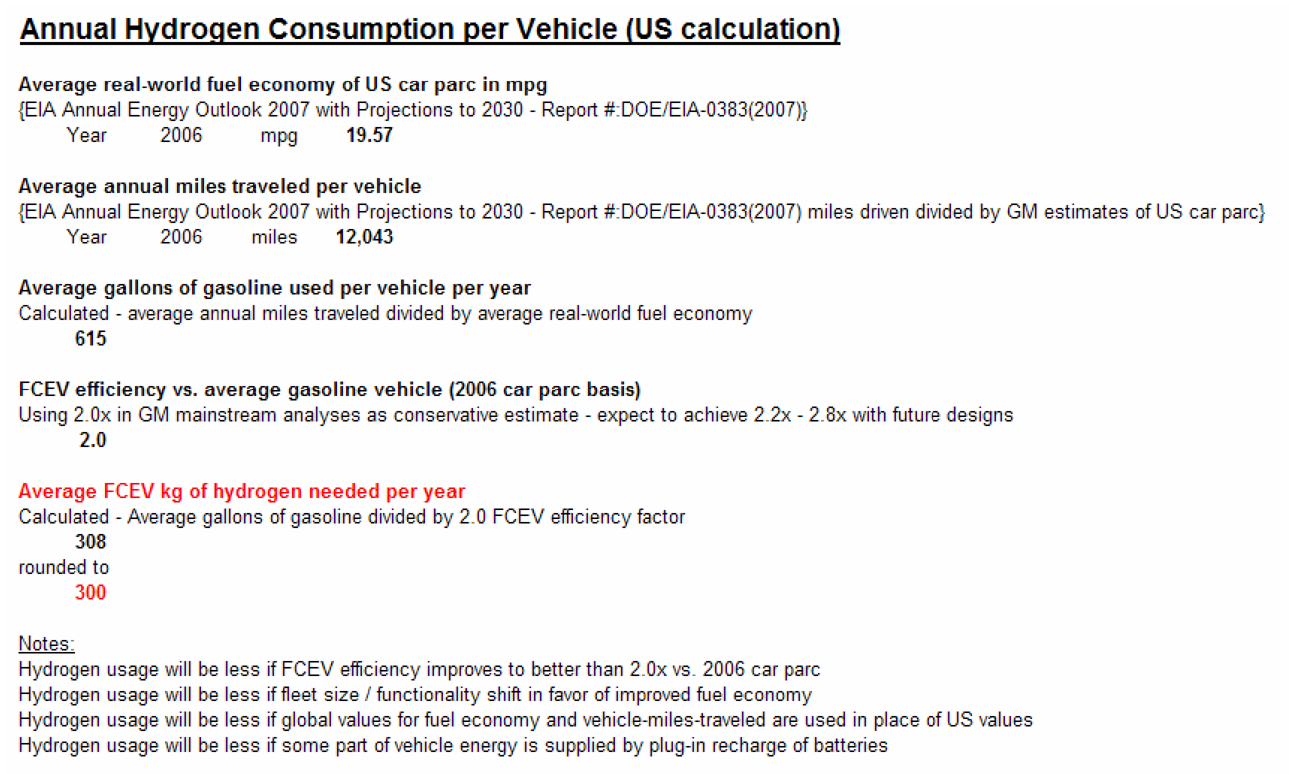
- Establish supportive hydrogen policies that are practical and ease permitting
  - Identify hydrogen-supportive communities, incentivize these communities, and proactively address "not in my backyard" (NIMBY) concerns.
  - Ease fueling station/service site permitting process in selected communities.
    - Ensure statewide consistency and local adherence to nationally-developed codes and standards (e.g. NFPA, ICC).
    - Educate local officials (fire marshals, local government) about hydrogen safety and best permitting practices.
    - Support the permitting of publicly accessible, major branded fueling stations.
    - Support cycles of learning and a broad array of options (e.g. overhead canopy storage, underground storage, on-site electrolysis or reformation, non-traditional fueling sites, 700-bar tanks).
  - Apply all hydrogen incentives broadly to all hydrogen feedstocks initially, including natural gas, to ensure successful adoption of FCEVs. Encourage renewable sources later after these pathways develop.

- Ensure that hydrogen fueling is available and affordable.
  - Coordinate infrastructure buildup with vehicle deployment plans with geographic strategy and timing.
  - Provide substantial incentives to hydrogen infrastructure providers, station owners/operators (e.g. credits, loan guarantees, tax incentives, emissions credits) to ensure that a minimum, convincing threshold of convenient fueling is available.
  - Provide hydrogen incentives to ensure a compelling price relative to gasoline – e.g. no hydrogen fuel tax until some percentage of market penetration is achieved (recommend 10 percent), plus additional incentives (since the price of the fuel will be a significant motivator for hydrogen FCEV sales).

- Educate consumers.
  - Promote hydrogen as a safe fuel, and promote the benefits of FCEVs for energy security and zero emissions.

# APPENDIX D. Calculations

## D-1. Annual Hydrogen Consumption per Vehicle



### Annual Hydrogen Consumption per Vehicle (US calculation)

**Average real-world fuel economy of US car parc in mpg**
{EIA Annual Energy Outlook 2007 with Projections to 2030 - Report #:DOE/EIA-0383(2007)}
Year 2006 mpg **19.57**

**Average annual miles traveled per vehicle**
{EIA Annual Energy Outlook 2007 with Projections to 2030 - Report #:DOE/EIA-0383(2007) miles driven divided by GM estimates of US car parc}
Year 2006 miles **12,043**

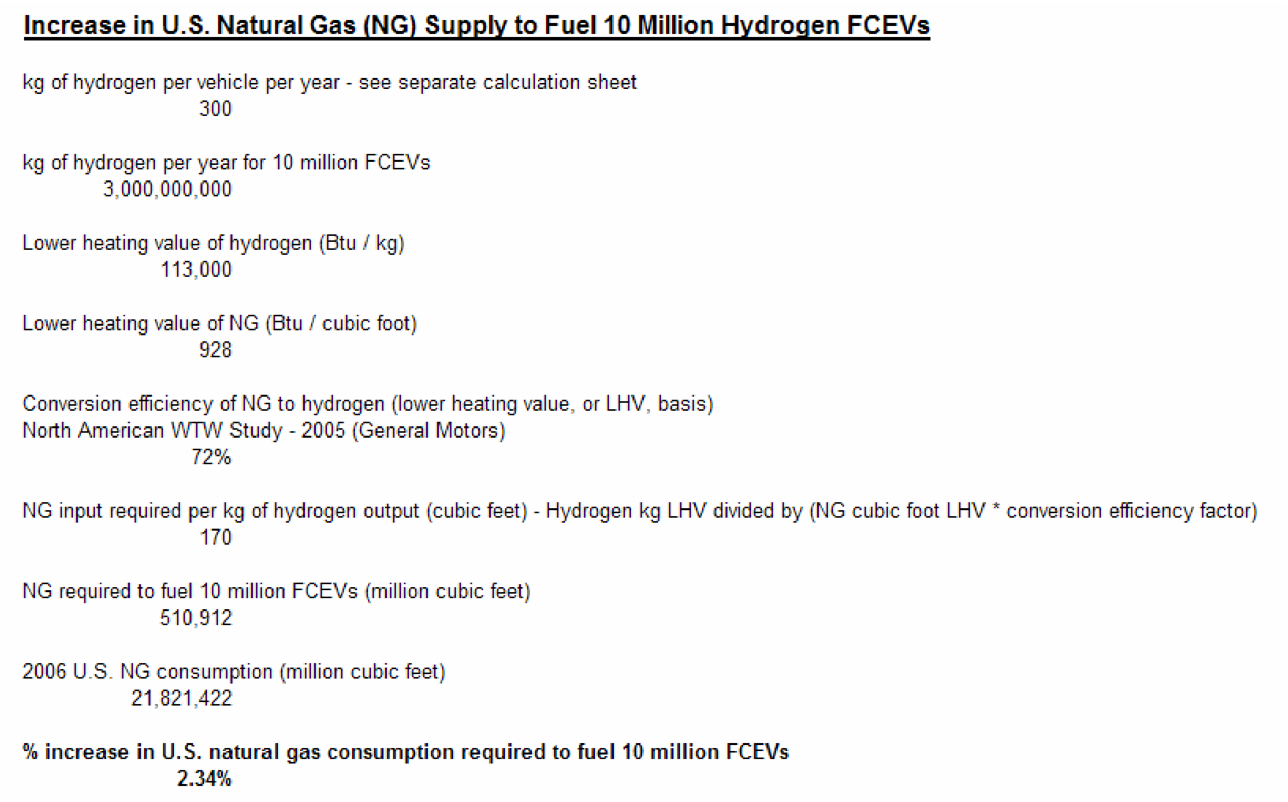
**Average gallons of gasoline used per vehicle per year**
Calculated - average annual miles traveled divided by average real-world fuel economy
**615**

**FCEV efficiency vs. average gasoline vehicle (2006 car parc basis)**
Using 2.0x in GM mainstream analyses as conservative estimate - expect to achieve 2.2x - 2.8x with future designs
**2.0**

**Average FCEV kg of hydrogen needed per year**
Calculated - Average gallons of gasoline divided by 2.0 FCEV efficiency factor
**308**
rounded to
**300**

Notes:
Hydrogen usage will be less if FCEV efficiency improves to better than 2.0x vs. 2006 car parc
Hydrogen usage will be less if fleet size / functionality shift in favor of improved fuel economy
Hydrogen usage will be less if global values for fuel economy and vehicle-miles-traveled are used in place of US values
Hydrogen usage will be less if some part of vehicle energy is supplied by plug-in recharge of batteries

## D-2. Increase in U.S. Natural Gas Supply to Fuel 10 Million FCEVs



### Increase in U.S. Natural Gas (NG) Supply to Fuel 10 Million Hydrogen FCEVs

kg of hydrogen per vehicle per year - see separate calculation sheet
300

kg of hydrogen per year for 10 million FCEVs
3,000,000,000

Lower heating value of hydrogen (Btu / kg)
113,000

Lower heating value of NG (Btu / cubic foot)
928

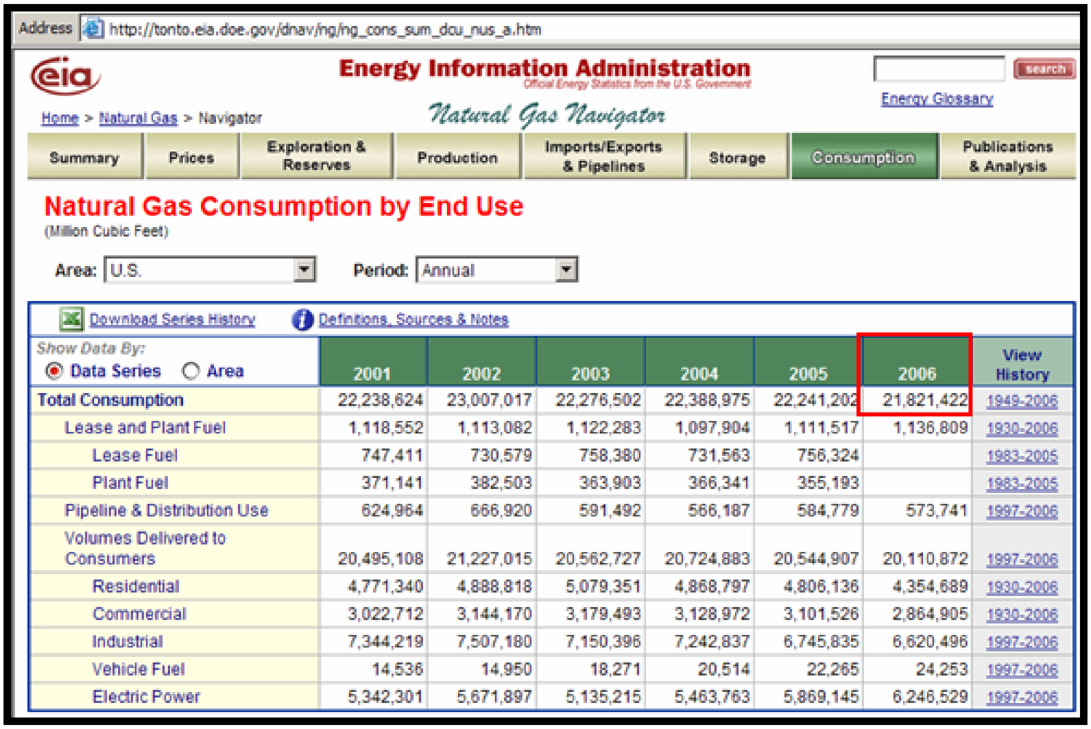
Conversion efficiency of NG to hydrogen (lower heating value, or LHV, basis)
North American WTW Study - 2005 (General Motors)
72%

NG input required per kg of hydrogen output (cubic feet) - Hydrogen kg LHV divided by (NG cubic foot LHV * conversion efficiency factor)
170

NG required to fuel 10 million FCEVs (million cubic feet)
510,912

2006 U.S. NG consumption (million cubic feet)
21,821,422

**% increase in U.S. natural gas consumption required to fuel 10 million FCEVs**
**2.34%**



Natural Gas Consumption by End Use
(Million Cubic Feet)

Area: U.S.
Period: Annual

Show Data By: ● Data Series ○ Area

| | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | View History |
|---|---|---|---|---|---|---|---|
| Total Consumption | 22,238,624 | 23,007,017 | 22,276,502 | 22,388,975 | 22,241,202 | 21,821,422 | 1949-2006 |
| Lease and Plant Fuel | 1,118,552 | 1,113,082 | 1,122,283 | 1,097,904 | 1,111,517 | 1,136,809 | 1930-2006 |
| Lease Fuel | 747,411 | 730,579 | 758,380 | 731,563 | 756,324 | | 1983-2005 |
| Plant Fuel | 371,141 | 382,503 | 363,903 | 366,341 | 355,193 | | 1983-2005 |
| Pipeline & Distribution Use | 624,964 | 666,920 | 591,492 | 566,187 | 584,779 | 573,741 | 1997-2006 |
| Volumes Delivered to Consumers | 20,495,108 | 21,227,015 | 20,562,727 | 20,724,883 | 20,544,907 | 20,110,872 | 1997-2006 |
| Residential | 4,771,340 | 4,888,818 | 5,079,351 | 4,868,797 | 4,806,136 | 4,354,689 | 1930-2006 |
| Commercial | 3,022,712 | 3,144,170 | 3,179,493 | 3,128,972 | 3,101,526 | 2,864,905 | 1930-2006 |
| Industrial | 7,344,219 | 7,507,180 | 7,150,396 | 7,242,837 | 6,745,835 | 6,620,496 | 1997-2006 |
| Vehicle Fuel | 14,536 | 14,950 | 18,271 | 20,514 | 22,265 | 24,253 | 1997-2006 |
| Electric Power | 5,342,301 | 5,671,897 | 5,135,215 | 5,463,763 | 5,869,145 | 6,246,529 | 1997-2006 |

# ACKNOWLEDGMENTS

The authors would like to thank Byron McCormick, Julie Beamer, and Lisa Horan for their insightful comments, suggestions, and contributions to our analysis and this paper. We would also like to especially acknowledge Larry Burns for his vision, direction, and direct contributions to the writing of this report.

## REFERENCES

[1] SRI Consulting. "CEH report Hydrogen." 2004.

[2] Argonne National Laboratory. "Assessing Current, Near-term, and Long-term U.S. Hydrogen Markets" http://www.dis.anl.gov/ceeesa/programs/hydrogen_markets.html

[3] U.S. Department of Energy. "Hydrogen Posture Plan." December 2006. Appendix B. http://www.**hydrogen**.energy.gov/pdfs/**hydrogen_posture_plan**_dec06.pdf

[4] D. Simbeck and E. Chang. "Hydrogen Supply: Cost Estimate for Hydrogen Pathways – Scoping Analysis." November 2002.
http://www.nrel.gov/docs/fy03osti/32525.pdf

[5] Davis S. C., Diegel S. W. "Transportation Energy Data Book." Edition 26, 2007.
http://cta.ornl.gov/data/index.shtml

[6] GE Global Research Media Center. "Global Research Receives Popular Mechanics 2006 Breakthrough Award"
http://www.ge.com/research/grc_7_1_14.html

[7] "A common position paper of BMW Group, DaimlerChrysler AG, Ford Motor Company, General Motors Europe AG, MAN Nutzfahrzeuge AG, Shell Hydrogen B.V., Total France and Volkswagen AG"
http://www.hyweb.de/News/Position_Paper_H2_Auto_Energy_OnePager_SEP2006.pdf

[8] Honda News Release. "Home Hydrogen Refueling Technology Advances with the Introduction of Honda's Experimental Home Energy Station." November 14, 2005.
http://world.honda.com/news/2005/c051114.html

[9] EIA. "Electric Power Annual 2000." Table 7.
http://www.eia.doe.gov/cneaf/electricity/epav1/epav1.pdf

[10] Brinkman N., Wang M., Weber T., Darlington T. "Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions." May 2005

[11] U.S. Department of Energy. "Hydrogen Production Technology"
http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.html