Rollout Strategy Topic Team Report

California 2010 Hydrogen Highway Network

January 5, 2005

The Rollout Strategy Topic Team Report was a collaborative effort by many people, some of whom contributed focused sections or passages involving specialized areas of expertise. The participation of and contributions from individuals represent neither an endorsement of the Report and its findings or recommendations, nor a verification of a review of the Report, by the individuals or the organizations they represent.

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1. Summary

The Rollout Strategy Topic Team is one of the five teams assembled to lay the groundwork for the development and initial deployment of the California Hydrogen Highway Network (CA H2 Net), as envisioned by the Governor's Executive Order S-7-04.

1.1 Goals

The Rollout Strategy Topic Team goals, which evolved substantially during the process, were condensed to:

Goal 1: Identify the technologies which produce and use hydrogen, their costs, and technology readiness for the three specific phases; now, by 2010, and beyond 2010

Goal 2: Establish siting criteria to implement hydrogen stations throughout California

Goal 3: Develop proposals to accelerate the commercialization of hydrogen in California utilizing mobile and stationary technologies

1.2 Blue Print Topic Team Framework

The Rollout Strategy Topic Team is made up of more than 80 participants, broken down into four subgroups: Production and Distribution, Applications, Sites, and Commercialization. Each of these subgroups has two subgroup leaders. The subgroup leaders, co-chairs, and managers of the Rollout Strategy Topic Team make up the "Core" group, as reflected in Figure 1-1.

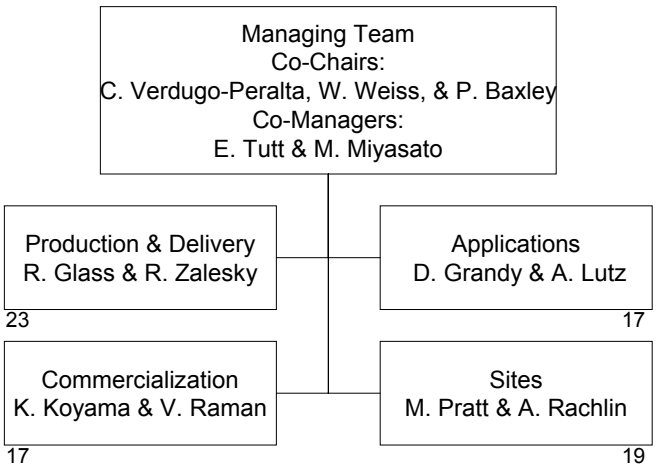


Figure 1-1. Rollout Strategy Team Structure

The timing to be considered in all of the subgroups was based on three phases: now, by 2010, and beyond 2010. Costs, industry readiness, network development and other considerations were considered within these timeframes. In addition, the subgroups were asked to identify the requisite actions necessary to implement the CA H2 Net by 2010 given three scenarios of vehicles: (A) 2,000, (B) 10,000, and (C) 20,000.

1.3 Production and Delivery

The Production and Delivery subgroup evaluated the various options for hydrogen production and delivery in terms of availability/industry readiness, technical and economic barriers, and environmental impacts and considerations. The focus was on production options that can eventually assure energy security and clean air for California. Both centralized and distributed production of hydrogen were considered in the comprehensive analysis. The various production options evaluated were:

- Electrolysis
- Reforming (principally of methane and methanol)
- Photobiological and photoelectrochemical
- Biofermentation
- Pyrolysis and gasification of biomass and coal
- High temperature thermochemical
- Membranes

Near-term (now to 2010) technologies of reforming (both centralized and distributed) and electrolysis are likely to contribute most significantly to the early stage development of the CA H2 Net because these established technologies leverage the existing electricity grid and natural gas pipeline infrastructure. Delivery options include truck, mobile refuelers, and to a limited extent, pipeline. However, in order to foster development and deployment of the CA H2 Net, all technologies should be considered and continue to be evaluated.

1.4 Applications

The Applications subgroup has cataloged potential hydrogen powered applications, analyzing them in terms of technology readiness, estimated cost, societal benefits, deployment barriers, potential customer benefits and acceptance, and possible rollout timing. When combined with information from the Economy and Societal Benefits Topic Teams, this should provide a basis for projecting specific numbers, costs, and benefits of hydrogen fueled applications in California.

There are challenges with the introduction of hydrogen fueled applications. These run the gamut from technological issues requiring more research and development to customer acceptance issues as product performance differs from current offerings, to the chicken-and-egg problem with hydrogen vehicles and hydrogen refueling stations.

Of the applications categories examined, all have at least one example of a product that is in the demonstration phase today. Also, all of the categories examined have a

product from a company that claims to currently be in limited production, although this is controversial, especially among competing suppliers. The point is that there are product announcements almost every day. However, not all of the information we might wish to report is publicly available. In addition, a wide range of products are presently in development, with near term plans for manufacture and sale.

The main technology drivers are hydrogen fuel cell vehicles and hydrogen internal combustion engine (ICE) vehicles. All of the major automobile manufacturers are working toward developing vehicles using either (or both) of these power plants with significant investments in research, development, and demonstration of hydrogen fuel cells and ICEs. Demonstrations are already occurring throughout California, Canada, the European Union (EU), and Japan.

Niche products and applications are finding customers, and while these do not represent large volumes of product, or of hydrogen utilization, they pave the way for more products, as well as increased hydrogen throughput, which lowers the price, making these applications more cost-effective. Recently introduced products may also allow leveraging of the existing compressed natural gas (CNG) network to start the hydrogen refueling system using H2/CNG blends. In addition, the existing CNG, heavy-duty vehicle fleets or stationary engines may provide increasing throughput to help develop the nascent hydrogen market.

Stationary fuel cell applications are expected to lead mobile fuel cells into the marketplace, due to the relatively large number of niches in energy systems for buildings, e.g. base load, backup power, and premium power, unlike mass-produced vehicles. Further, distributed generation (DG) using hydrogen or hydrogen-natural gas blends in stationary ICE generators could find market niches in the near-term. As DG continues to offer advantages for on-site power applications and relief of grid congestion, these stationary hydrogen technologies should be seriously considered.

Various incentive mechanisms available to government can be strategically applied for maximum effect by close examinations of the product markets they are designed to influence. Finding the best opportunities where products and their markets are at critical tipping points, will produce the most leverage. Some of these opportunities are known. But as we bore further into the details of how to apply the resources available, the work would benefit from further analysis to better predict the effect of proposed actions. This analysis, however, is beyond the scope of this phase of initial activity and should be considered as the CA H2 Net effort progresses.

1.5 Sites

The Sites subgroup was established to develop the site identification process. Successful deployment of hydrogen vehicles in California requires a network of hydrogen fueling stations to be placed in strategic locations for maximum utilization. This will enable regional (inter-city), inter-regional, and ultimately inter-state travel.

The Sites subgroup developed the selection process for new hydrogen fueling stations and distributed generation sites in California. The station technology or form of fuel (liquid, low or high pressure hydrogen, HCNG, etc.) was not identified since this was considered a product of the siting process.

To develop and shape the screening and selection process, three primary goals for hydrogen fueling station placement were established: (1) Maximize network development and reliability; (2) maximize the number of stations accessible to a maximum number of consumers, and (3) operate each location with a high percentage of fuel utilization, demonstrating maximum hydrogen fuel throughput.

The site identification process established a variety of important screening criteria to guide final site selections. Two key success factors were considered in establishing a site. The first is to ensure sufficient utilization by deploying vehicles or hydrogen-DG at the station location. The second success factor is to ensure the commitment of the site host partner. It is essential that the host partner be committed by demonstrating long term, top down management support. Further, it is important that the host partner have a local on-site champion so that together with top management support the organization will overcome the numerous challenges of introducing a new technology.

A total of 19 different types of host fleets and potential locations were identified. A comprehensive set of screening criteria was also established. The screening categories include: Ability to serve a maximum number of users; Strategic location; Safety; Economic factors; Experience with gaseous and alternative fuels; and Logistical Issues.

To achieve the targeted goals, station development is expected to initially leverage a fleet-based strategy in the near-term with transition considerations toward a full retail market. Combined with existing, planned, and anticipated hydrogen stations, early stage development will focus on regional network clusters in larger cities such as San Diego, the Los Angeles Basin (South Coast AQMD territory), Sacramento, San Francisco and the San Joaquin Valley. Ultimately, these regional clusters will be bridged to form a comprehensive state network. For illustrative purposes, three hydrogen station scenarios (50, 150, and 250 stations) have been mapped. Based on population and retail gasoline station densities, these three maps reveal how the regional clusters and statewide network might appear. San Joaquin Valley clusters were not included in the maps due to time and resource constraints, but will be reflected in the future. The next stage of network development requires careful screening and evaluation of the targeted site host fleets.

To develop the network of hydrogen stations, strategies, as well as obstacles and barriers are considered. Ultimately, the implementation plan provides direction on refining network site opportunities along with State initiatives that will facilitate and hasten the creation of the California Hydrogen Highway.

1.6 Commercialization

The Commercialization subgroup adopted a goal to identify steps to accelerate the commercialization of hydrogen technologies in support of implementing the CA H2 Net by 2010. A "business-as-usual" approach was not considered aggressive enough to achieve the higher vehicle scenarios (B and C), and so the subgroup decided early in the process to consider all possible accelerators, including politically sensitive ones.

To gather a diversity of views, 18 participants gathered through numerous meetings and conference calls to generate ideas. These participants represented energy companies, automobile manufacturers, fuel cell suppliers, as well as government agencies. Although over 20 ideas were initially discussed, the six high priority items are presented here:

1. *Standardize the statewide permitting process for hydrogen fueling stations. The subgroup believes this type of activity can occur by 2010.*

2. *Capture greater economies of scale for distributed hydrogen production from reformers and renewables such as wind and photovoltaics. The subgroup believes this can be accomplished now if reliability and cost challenges can be overcome.*

3. *Capture greater economies of scale for fuel cell stack production. This activity will take time to implement and will depend on the demand for fuel cells, the cost to manufacture, and the overall product cost.*

4. *Develop and initiate government assistance, i.e., incentives, tax credits, new legislative policies, etc. This activity can be initiated now given the appropriate political will, leadership and resources*.

5. *Develop a revenue source and utilize proceeds to fund incentives for vehicles. Similar to the above recommendation, this activity can be initiated now but also requires the appropriate political will, leadership and funding resources.*

6. *Ensure public access to refueling stations. The subgroup believes this activity can be initiated now with the fueling station projects already underway. This can also assist with positive public education of hydrogen and therefore dispel unwarranted fears found in previous news articles.*

In addition to these six high priority actions, the subgroup also developed a chronology of lessons learned from previous alternative fuel introductions.

1.6.1 Lessons Learned from Prior Alternative Fuel Vehicle Programs

Since the early 1980s, California has made several attempts to expand the fleet of alternative fuel vehicles to help improve air quality and reduce petroleum dependence. While previous efforts may be construed as less than successful, California still has the largest and most diverse alternative fuel vehicle fleets and infrastructure of any state in the nation. These alternative fuel introductions have occurred through specific fleet

applications, as well as building appropriate infrastructure to support these vehicles. To introduce hydrogen as an alternative fuel to petroleum, the stakeholders will need to ensure that the lessons learned from the previous programs are well understood.

Based on California's experience with previous alternative fuel vehicle programs, building fueling stations in anticipation of a future influx of vehicles (the "build it and they will come" theory) can lead to stranded investments. Such investments also represent opportunity costs that reduce more effective programs.

Near-term successes are very important even if it is limited to niche applications. The natural gas vehicle model may be the only real success so far for alternative fuel vehicles capturing markets niche by niche. This success may not transfer to the larger vehicle population.

Based on these lessons, public-private partnerships are deemed critical with sufficient incentives to all stakeholders to ensure the highest probability of success, especially in the early stages of deployment. Since there has been no successful alternative fuel introduction that has transitioned to the retail market, sustained and clear leadership with strong public-private partnerships will be essential.

1.7 Recommendations

The Rollout Strategy Topic Team suggests three overarching recommendations with more specific recommendations presented within the text of the subgroup reports. The three umbrella recommendations are discussed below.

1.7.1 Formalize the Organization

Instead of the ad hoc group of volunteers assembled for the initial process, the organization of the CA H2 Net should be formalized into a structure empowered to

- Coordinate and drive the effort by expanding established momentum
- Build on and strengthen constructive involvement of stakeholders
- Steer and adapt the program based on observations and learnings
- Coordinate and leverage external hydrogen initiatives (other U.S. states, Canada, Japan, EU)
- Investigate opportunities to integrate into the California Performance Review
- Establish a statewide Hydrogen Ombudsman
- Consider legislation, policies, and an executive order to foster development of the CA H2 Net

In order to implement many of the recommendations coming from this and other Topic Teams, a formal organizational structure with adequate resources will be required. For example, selecting the technologies for stations and applying the siting criteria will require dedicated staff resources. This staff should also be tasked with monitoring the implementation rollout to ensure the greenhouse gas and criteria pollutant goals are met.

This organization could also ensure the integration of the stations into a real network where communication of data is provided to all the stakeholders (OEMs, energy providers, agencies, and outside organizations, states and/or countries). This will allow the OEMs and energy providers the ability to optimize placement of stations and vehicles. This would also provide high level visibility for rollout, as well as attract leveraging possibilities with other entities.

1.7.2 Mechanics of Implementation

In order to enhance the success of the CA H2 Net, careful attention must be paid to the implementation of the early station deployments. Based in part on previous alternative fuel introductions and the limited hydrogen experience, the Rollout Topic Team offers these recommendations:

- Focus initial infrastructure in and between the highest expected vehicle/population centers, (i.e., the four county Los Angeles Basin, San Francisco, Sacramento, and San Diego)
- Maximize station utilization and experience gathering. Widely communicate these findings to foster positive public outreach and efficient implementation of codes and standards to the jurisdictional authority
- Utilize, to the extent possible, past learnings with alternative fuel deployments
- Sponsor improved models for station siting and encourage industry, as well as university involvement
- Leverage existing hydrogen generation and fueling assets (e.g., CNG, gasoline, merchant hydrogen)
- Expand and adapt networks as vehicle population grows

These actions will allow flexibility while providing an integrated effort versus pockets of disjointed demonstrations.

1.7.3 Leveraging

In order to fully capitalize on the current process, which involves the automobile manufacturers, energy providers, station builders, and government agencies, strategies should be implemented to leverage and springboard off the current momentum. Several of these recommendations are listed below:

- Establish Public-Private partnerships in each metropolitan region identified above, with wide stakeholder participation for “coordinated differentiation” in each region. This could involve distinct government (local, state and/or federal) and industry (auto, energy, supplier) consortiums in each region with limited participation. The strategy is to establish champions in each area which take advantage of different station technologies, utilization via vehicles and stationary, and government participation such that distinct learnings are offered by the different regions. Although these regions are different in geography, population and resources, the information should be communicated throughout the one point of contact, the State, in order to ensure coordinated efforts and reduced duplication.

- Identify industry and government agency incentives, financial and other, in order to reduce the risk and uncertainty of future liability to all stakeholders. For the early deployment of the CA H2 Net, government leadership is critical in order to reduce the risk the manufacturers, energy providers, and station operators will perceive. A coordinated, formalized organization will be able to analyze and adapt the best ideas from approaches used in Europe (i.e. “Lighthouse Projects”), Japan, and even recent DOE Infrastructure Demonstration projects.

- Work with other agencies, states, and countries to leverage resources and experiences. There are several different organizations and countries working on hydrogen and fuel cell projects. The CA H2 Net should work closely with these entities to coordinate efforts and leverage resources. For example, a joint request for proposals for vehicles could be released with the vehicles used simultaneously or shared in a series in various countries. Joint or similar policies or codes and standards could be adopted to ease siting and fueling concerns, as well as spur increased vehicle production.

- Establish high school and community college curricula, as well as university research programs, regarding hydrogen, fuel cells for both stationary and mobile. The future of the energy transition will depend heavily on scientific perseverance (continued research) and valuing of externalities (public education), especially through outreach to the next generation of leaders. Establishing this foothold in high schools and college science curricula will be an important investment.

- Establish first responder curricula for fire science courses at the community college level in addition to ongoing courses for existing fire fighters and EMT personnel, regarding hydrogen, fuel cells and hydrogen ICE vehicles.

2. Hydrogen End-Use Applications

2.1 Introduction

This section of the Rollout Strategy Topic Team report catalogs the potential hydrogen powered applications in the three timeframes being considered – now, 2010, and forward. Both mobile (e.g., fuel cell vehicles) and stationary (e.g., energy stations) applications are considered. Each potential application is reviewed in terms of its technology readiness, estimated cost, societal benefits, deployment barriers, potential customer benefits and acceptance, and possible rollout timing. When combined with information from the Economy and Societal Benefits Topic Teams, this could provide a basis for projecting specific numbers, costs, and benefits of hydrogen fueled applications in California.

The review is deliberately broad based. For example, we consider hydrogen ICEs (including possible small vehicle manufacturer conversions) as well as fuel cell vehicles. In addition to large and small energy stations, hydrogen applications ranging from agricultural pumps to small consumer products have been examined. Infrastructure strategies and issues such as vehicles fueled with hydrogen and natural gas blends, hydrogen co-production, hydrogen storage technologies, and fueling station options are also considered.

We also attempt to be unbiased, and do not pick winners and losers. We observe what products appear to be at various stages of commercialization, and note some of the conditions put forth by the manufacturers of those products that they feel would benefit their business.

The review is organized by the following categories:

- Vehicles
- Stationary Applications
- Refueling Stations
- Fuels Applications
- Portable/Consumer Applications
- Storage Systems

Some general conclusions can be drawn from the work. Of the applications categories examined, all have at least one example of a product that is in the demonstration phase today. Also, the majority of the categories examined have a product from a company that claims to be currently in limited production, although this is controversial. Reaching the stage of “full production” or “commercialization” proved to be the most controversial, as it is even difficult to reach a common definition. The criteria for determining this state vary by company, yet there is a general understanding of the concept.

Products, as they are developed from idea to full production by multiple competitors in a mature marketplace, move through various stages. At first, there is a conceptual stage that moves into demonstration through prototypes. If the prototypes are successful, there is a transition phase involving the production of multiple copies of that product where cost, consumer acceptance, manufacturing feasibility, and other issues are worked out. Finally, with success in that stage, the product moves into a commercialization stage, marked by full production, competitors entering the market, and an increase in consumer demand. This concept, as it applies to products using hydrogen fuel, is illustrated in Figure 2-1:

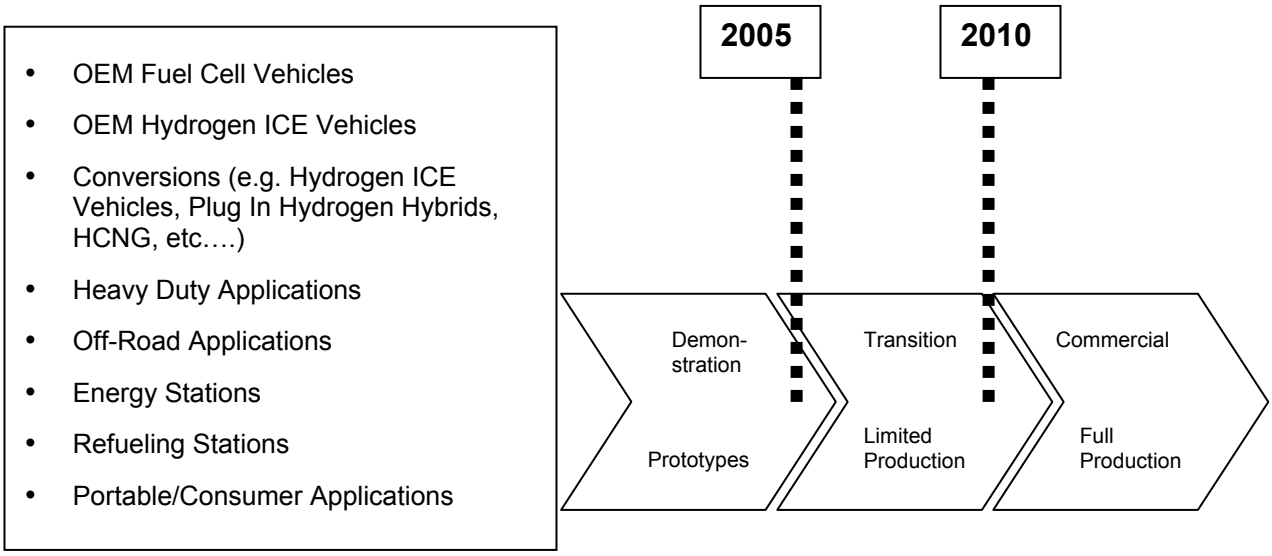


Figure 2-1. Rollout Timing — Earliest Technology Readiness

It is important to examine the technological readiness of various hydrogen-consuming new products in order to have a basis to examine what governmental policy actions will be productive to accelerate commercialization of these products, so that society can reap the benefits.

The reader is referred to Table 2-6, Hydrogen End Use Applications, for the details on the state of commercial development of the many products reviewed.

The review of hydrogen fueled applications leads to observations, revealing several strategic opportunities and recommended actions:

- Hydrogen fueled internal combustion engine vehicles, either as straight hydrogen ICEs, or hydrogen ICE-HEVs, can be available in significant numbers much sooner than fuel cell powered cars. Encourage the deployment of internal combustion engine vehicles using hydrogen fuel for early-on populating of the Hydrogen Highway. Fuel cell vehicles are expected to take their place in the vehicle fleet some years later, as and if they are ready.

- Small companies are able to get products to market faster than large companies, but large companies can produce products in larger numbers. Therefore encouraging small companies will get earlier deployments as well as foster competition, thereby demonstrating to the larger companies that there is consumer interest in these products, and causing them to make the necessary investments sooner. This can be accomplished by granting relief on expensive government and independent laboratory testing and certification processes. However, consumers generally prefer products from original equipment manufacturers, so market penetration will likely require large manufacturers.

- Installing hydrogen refueling stations at existing CNG sites with new products that make dual use of major components will allow a quick deployment of stations at CNG stations, and keep costs to a minimum. This will result in a significant number of refueling stations early on to encourage vehicle purchases. It will minimize the cost of "stranded assets" during the early years of the deployment while throughputs are still low.

- Allow manufacturers of refueling equipment to finance the government's purchase of that equipment. This will eliminate the need for government funds to be invested, and can be accomplished by agreeing to purchase a quantity of natural gas for the fleet from that vendor – purchases which may be made anyway.

- Portable, off-road, and other hydrogen applications are proliferating, and encouraging these could potentially enable a product or products to catch on with the consuming public, dramatically expanding the hydrogen market.

- Encourage technologies that increase efficiency, for example, plug-in hybrid vehicle technology. In this way the ultimate size of the prime mover, the most expensive component can be reduced, lowering the cost of the finished hydrogen powered product, and making the overall market transformation more achievable. Also, this reduces the amount of hydrogen needed, and consequent well to wheels emissions.

- Blend hydrogen with natural gas at existing CNG refueling stations. It will further reduce vehicle emissions, while increasing the throughput of hydrogen in production, working to lower the cost. While existing NG vehicles may have to be modified to burn the blended mixture, availability of the blend will provide access to more vehicles.

- Encourage the early development of stationary and off-road applications. These installations are already finding cost-effective niches in a surprisingly broad array of situations. Proliferation of these installations will:

  - Improve air quality
  - Increase throughput of hydrogen fuels and hydrogen carrier fuels
  - Provide a slipstream of hydrogen to supply a vehicle refueling station

- Increase volume of fuel cells and other hydrogen applications manufacturing, reducing price
- Help stabilize and reinforce the electricity distribution grid
- Increase the reliability and quality of power to the facilities

In the process of communicating with companies making products that run on hydrogen fuel, the team heard further recommendations originating with those companies that the group felt worthy of listing. These are:

- Encourage the Governor to challenge industry to build, and California residents and state government to buy, hydrogen-fueled cars.

- Provide consumer and manufacturer subsidies – predictable and declining

  - Tax credits
  - Tax deductions
  - Carl Moyer grants
  - Capital cost buydowns
  - Emission Reduction Credits
  - Increase current spending on existing public goods programs
    - Focus strategically
  - Provide time and money to advance R&D

- Enable markets for hydrogen products through government testing and certification and Codes & Standards development.

- Develop projects at government facilities with a high public visibility profile

  - Stationary fuel cells at government sites
  - Purchase hydrogen vehicles for government use

- Develop financing mechanism(s) to cover incremental cost to be competitive with non-hydrogen products

- Provide a supportive regulatory environment for all hydrogen stationary applications by making available Power Purchase Agreements and Streamlined permit approval processes

- Reach out to the public and special groups

  - Public officials informed about societal benefits of hydrogen and code implementation issues
  - Educated public comfortable w/ hydrogen in various applications
  - Hydrogen components inserted into K-12 education curricula
  - Celebrity endorsements

- Provide special preferential treatment for hydrogen vehicles, such as access to high-occupancy vehicle lanes and preferential parking.

- Make recommendations to the federal government:

  – Include hydrogen fueled vehicles in CAFE standard compliance calculations, using some multiple of the gasoline equivalent of the hydrogen mileage, as is currently done for alternative fueled vehicles such as ethanol vehicles.

2.2 Background

The Applications subgroup was one of four subgroups of the Rollout Strategy Topic Team. Its mission was to:

- Develop a catalog of hydrogen applications and their characteristics for the purpose of assessing the technology and industry readiness

- Identify and evaluate technology deployment and fuel consumption opportunities

- Ascertain whether these applications will benefit from specific actions by the Governor, the state government, or the Hydrogen Highway working group to move to the next stage of development: research, demonstration, or commercialization

To this end, the group has met regularly through telephone conference calls, participated in smaller group meetings in person, interacted with other Topic Teams and their subgroups, worked with the other leadership and advisory teams in the Hydrogen Highways effort, and sent a great deal of e-mail to each other. The team members, all volunteers, hail from government, industry, academia, and various consultancies.

The information on Table 2-6 at the end of this section gives details about the various hydrogen-using applications considered. This text provides a general overview of each of the technology categories, as well as some clarifying comments about the chart entries. This review focused on the timeframes from now until 2010, a snapshot at 2010, and beyond 2010.

The analysis is organized into the following categories: Vehicles, Stationary Applications, Refueling Stations, Fuels Applications, Portable/Consumer Applications and Storage Systems.

As was mentioned in the Introduction, the presentation of data on the state of commercial readiness of various technologies became controversial, particularly as the attempt was made to add together information from different companies on the same topics. The timing of the onset of full production was the most controversial, for the following reasons.

First, as the product data represent forecasts, they are probably wrong to some extent. Second, some companies may be more bullish on their forecast than others in order to

encourage sales. Third, some companies may be conservative in their forecasts or even not admit to having such products under development, as this is highly sensitive competitive information. Fourth, each company has a unique view of how their statements will position the company in the marketplace, and has their own strategy for deploying new products.

The definitions of “demonstration,” “limited production,” and “full production” are difficult to pin down with any precision. Again, each company has a unique set of criteria that defines how they roll out new products. This can vary widely from a new startup company needing to attract investors, to a well-established large company, concerned about maintaining their high credibility with consumers. All seem to have a concept of these various stages of product development and commercialization, but a common definition proved elusive. Consequently, adding together data from different companies to present summary information with any accuracy, and so the reader is referred to the Appendix for the product-by-product details.

In the following sections, an overview of each product category is provided for background and clarification of the material in the Appendix.

2.3 Vehicles

2.3.1 Fuel Cell Light-Duty Vehicles

Hydrogen powered Fuel Cell Vehicles (FCV) offer the promise of clean, efficient transportation, with the possibility of reduced dependence on fossil fuels. FCVs also have a very high “tank-to-wheel” efficiency, and where hydrogen is derived from renewable energy, can achieve a zero “well-to-wheel” emission cycle. For these reasons, almost every major automobile manufacturer has made significant investments in developing fuel cell technology. Significant technological, cost, and market challenges for wide retail market adoption within the 2010 timeframe include:

- Cost of fuel cell stack and balance of plant
- Durability of the fuel cell stack relative to ICEs
- Fuel cell stack performance
- Onboard hydrogen storage (common with all hydrogen vehicle applications) resulting in a reduced driving range between fuelings.

The recent market introduction of gasoline hybrid electric vehicles (HEVs), such as the Prius, has increases the challenge for FCVs. HEVs currently offer the consumer a low cost, low emissions, more fuel-efficient option. When considering the overall “well-to-wheel” energy cycle, gasoline hybrids compare quite well to current FCVs. For example, although the vehicle efficiency of a FCV is higher than a HEV such as the 2004 Prius, when the efficiency of producing hydrogen versus gasoline is factored in, the overall well-to-wheel efficiency (i.e., the well-to-tank efficiency multiplied by the tank-to-wheel efficiency) of the Prius is higher. (See Table 2-1.) [1]

Table 2-1. Toyota's Well to Wheel Efficiency Estimates (Internal data from Toyota Motor Sales, Inc.)

Vehicle Type	Well to Tank (%)	Tank to Wheel (%)	Well to Wheel (%)
Gasoline Vehicle	88	16	14
Gasoline Hybrid	88	37 (Prius)	32[a] (Prius)
Hydrogen FCV	58[b]	38[c]	22
Hydrogen Hybrid FCV	58[b]	50[c]	29*[3]
Hydrogen Hybrid FCV (Target)	70	60	42*[3]

[a] Japanese 10 – 15 mode Toyota's estimation (confirmed by Argonne National Lab)
[b] Natural gas base
[c] Measurement from the electric current

However, gasoline HEVs still depend on fossil fuels and ultimately cannot address resource depletion. Furthermore, FCV efficiencies can also be improved with hybrid technology currently being applied to gasoline vehicles. FCV well-to-wheel efficiencies will further increase as hydrogen production efficiencies are improved. Finally, fuel cell vehicles can potentially achieve a zero well-to-wheel emissions cycle, while simultaneously addressing resource depletion issues, which gasoline cannot. However, given current technology, this can only occur if hydrogen is produced via electrolysis from renewable energy sources.

In summary, given their overall energy efficiency and emissions improvement potential, coupled with the potential of a fuel that can be derived from multiple sources, FCVs still offer one of the best transportation prospects in the mid to long-term.

A survey performed by the California Fuel Cell Partnership estimates that up to 300 fuel cell vehicles could be in circulation by 2008 and that this could be increased by a factor of up to 8 times by 2012 depending on technology advancements.

In addition, the DOE DFCIT program is sponsoring a fleet demonstration that is expected to place approximately 10 to 20 vehicles in the Southern California area.

The Fuel Cell 2000 website provides a wealth of information on fuel cell light-duty vehicles [2].

2.3.2 Specialty Vehicles

2.3.2.1 Mass Transit Buses — Fuel Cell and ICE Powered

Hydrogen fueled transit buses are the only fuel cell vehicles (indirectly) required by State regulations at this time. The ARB Transit Fleet Rule gave large transit agencies the choice of natural gas or clean diesel tracks. Agencies choosing the clean diesel

track are required to deploy a specified number of Zero Emission Vehicles (ZEV) buses, and hydrogen fuel cell buses are the most credible ZEV candidates. A few hydrogen fueled buses are currently undergoing testing at California transit agencies, and several more are planned for revenue service before 2010. Technologies being tested at this time include four fuel cell buses, four hybrid electric/fuel cell buses (one of which is a plug-in hybrid) and one hybrid electric/hydrogen ICE bus. The number of fuel cell and other types of hydrogen buses deployed in the future will depend on the success of current test programs, technology advancements, cost reductions, and potential modifications to the ARB Transit Fleet Rule. Cost is a major impediment to implementing these vehicles. A fuel cell bus is as much as 10 times the cost of a diesel bus and a hybrid electric/hydrogen ICE is 2 to 3 times the cost of a conventional diesel bus. On the other hand, societal benefits are substantial because hydrogen buses replace diesel buses, which have NO_x and toxic particulate emissions that are orders of magnitude higher than those from light-duty gasoline ICE vehicles with three-way catalysts.

The References contain links to further information on hydrogen fueled buses [3].

2.3.3 Miscellaneous Vehicles

Implementing the CA H2 Net has many potential benefits in terms of enabling fleets of hydrogen vehicles and utilizing stationary power plants. An additional benefit is the added hydrogen availability for non-traditional vehicles such as ferries, material handling equipment (e.g. forklifts), utility vehicles (e.g., John Deere Gators), hauling vehicles, and scooters. Some of these applications can have an impact on the local environment as well as offer alternative transportation opportunities. At this time there are few of these applications planned for California, but the implementation of hydrogen refueling infrastructure will encourage their growth.

Vehicles other than buses are also finding niches. In general, their potential for significant contribution to deployment of the Hydrogen Highway is much smaller than buses. However, they are providing important experience with fuel cells in a variety of environments. They also increase the possibility of reducing the cost of manufacturing fuel cells by increasing the production volume.

The references contain links to further information on a variety of specialty vehicles, including niche transportation (aerospace, bicycles, industrial vehicles, railways, scooters and space, as well as marine and underwater applications) [4].

2.3.4 Hydrogen ICE Vehicles

Hydrogen internal combustion engine (ICE) vehicles are a promising option and pathway for reducing transportation fuel cycle emissions of air pollutants and dramatically reducing greenhouse gases, while reducing dependence on petroleum. Like hydrogen FCVs, the air pollutant emissions from hydrogen ICE vehicles are to a large extent a function of how the hydrogen with which they are fueled is produced, but unlike FCVs they also can produce some additional emissions associated with the combustion of hydrogen. These “engine out” levels of pollution are typically very low

due to engine operation strategy and exhaust aftertreatment. Hydrogen ICEs offer the potential for initiating a transportation market for hydrogen in advance of FCV commercialization.

Manufacturers known to be currently involved in or investigating hydrogen ICE vehicle development include at least the Ford Motor Company, BMW, GM, as well as small vehicle manufacturers such as the Hydrogen Car Company, ECD-Ovonics, and Quantum. Some of these companies have announced plans for various hydrogen ICE models in 2005. For example, Ford has announced both a V-10 shuttle bus and a hydrogen hybrid electric station wagon and ECD-Ovonics has indicated an offering in 2005. There appear to be no major issues associated with commercialization of hydrogen ICE vehicles, with no radical new technologies needed, although progress in on-board hydrogen storage is needed in order to provide consumer performance and price transparency.

Under a South Coast AQMD project, 30 to 35 hybrid electric Toyota Prius vehicles will be converted to operate on hydrogen. Three vehicles have been converted so far, one with hydrogen stored in an Ovonic metal hydride and two with compressed gas storage by Quantum Technologies.

Table 2-2 compares fuel economy projections for hydrogen ICE vehicles. Where available, the projected fuel economy for an equivalent gasoline vehicle is given, as well. The studies look at both conventional-drive and hydrogen ICE vehicles. These studies generally show that fuel economy improvements of 20 to 60 percent are believed to be possible for hydrogen ICE vehicles relative to comparable gasoline vehicles, on a gasoline gallon equivalent basis.

With regard to key details of these studies, the GM European study [1] uses a 2002 Opel Zafira minivan with projected improvements in 2010 (such as mass reduction) as its platform, and tests with the European Driving Cycle (EDC) and an automated manual transmission. The conventional vehicles use an automated manual transmission, and the hybrid uses a parallel configuration with a full-sized engine and nickel-metal hydride (NiMH) batteries sized to meet a 20 km zero emission vehicle (ZEV) range. Arthur D. Little, Inc. [2] bases its results on a midsized vehicle, and uses a combination of city (FUDS) and highway (HFET) drive cycles. The Keller and Lutz [3] study is based on an Advisor model running a Toyota Prius modified with four-stroke, spark-ignited, hydrogen ICE on the federal urban driving schedule (FUDS). Geiss, et al., [4] conducted laboratory tests of a Prius modified with a hydrogen ICE running city, highway, and combined drive cycles. They looked at three configurations of the hydrogen ICE: turbo-charged and intercooled, supercharged, and naturally aspirated. The Thomas, et al. [5] study was based on a modified Mercury Sable, which was 270 kg lighter than a conventional Sable. It used a 1.25 times faster EPA 55/45 combined drive cycle.

Table 2-2. Fuel Economy Estimates for Hydrogen ICE and Conventional Vehicles

Study	Vehicle Description	Fuel Economy (mpgge)	Vehicle
GM European [5]	H_2 ICE vs. Gasoline — Conventional Vehicle	36.9 vs. 30.7[a]	Opel Zafira Minivan
GM European [5]	H_2 ICE vs. Gasoline — HEV	50.1 vs. 41.9[a]	Opel Zafira Minivan
Arthur D. Little [6]	H_2 ICE vs. Gasoline — Conventional Midsized Vehicle	~ 39 vs. ~32[b]	Midsized vehicle
Keller and Lutz [7]	H_2 ICE HEV	60[c]	Advisor Model
Geiss et al. [8]	H_2 ICE HEV (Prius) — Naturally aspirated	49.0[d]	Modified Prius
Geiss et al. [8]	H_2 ICE HEV (Prius) — Turbocharged and intercooled	42.3/46.1/43.9[e]	Modified Prius
Geiss et al. [8]	H_2 ICE HEV (Prius) — Supercharged	45.2/54.7/49.0[e]	Modified Prius
Geiss et al. [8]	Gasoline HEV	52/45/48.6[e]	Modified Prius
Thomas et al. [9]	H_2 ICE HEV vs. — Conventional Mercury Sable	~ 50 vs. ~30 [c]	Modified Mercury Sable

Notes:
[a] European driving cycle.
[b] Combination FUDS/HFET driving cycle.
[c] FUDS driving cycle.
[d] EPA City driving cycle.
[e] City/Highway/Combined EPA driving cycles.
[f] 1.25x accelerated EPA Combined driving cycle.

2.3.4.1 Plug-in Hybrids

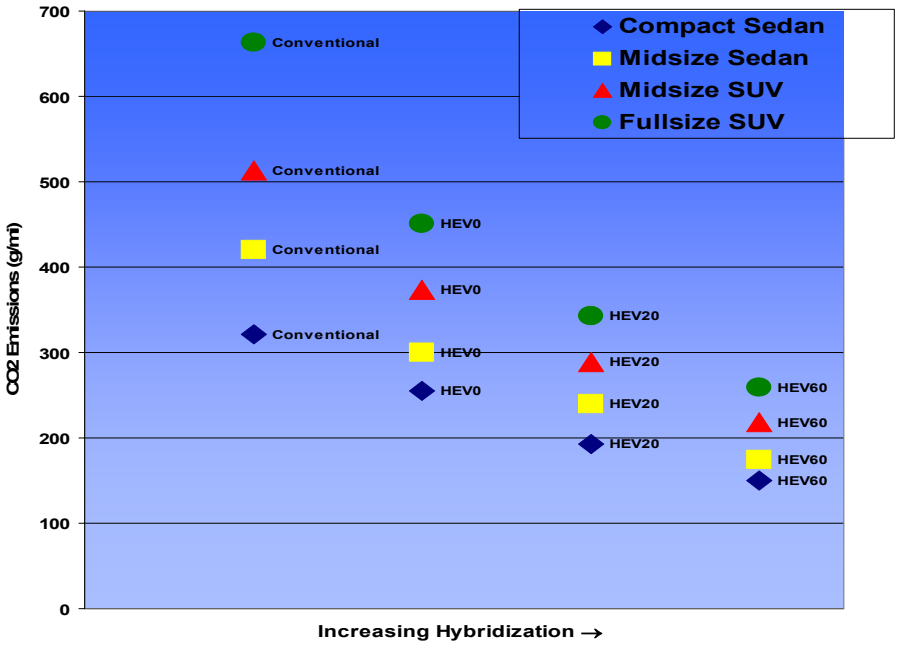
A "Plug-in Hybrid-Electric Vehicle" (PHEV) is a version of the now familiar hybrid-electric vehicle that has larger battery capacity to run for some period of time on batteries only, and also has the capacity to be charged by plugging into grid power, as well as by its own engine. While PHEVs are not, necessarily, a hydrogen-fueled application, the technology can be applied to hydrogen vehicles, and it is an important technology whose widespread adoption will greatly help in the move towards the hydrogen economy. Because of the efficiency improvements, this becomes an enabling technology to the very same emission, GHG, and energy independence goals that hydrogen seeks to achieve. While using gasoline, a PHEV configuration will result in substantial criteria pollutant, greenhouse gas, and petroleum use reductions (up to 90 percent reduction in engine-fuel consumption, tank-to-wheels). When using a hydrogen fueled internal combustion engine as its prime mover, its high fuel efficiency will reduce the impact of the cost of fuel. When using a fuel cell as its prime mover, it will further reduce the impact of fuel cost due to even higher efficiencies, but importantly, this technology will reduce the size of the fuel cell needed – the most expensive component.

Much of the PHEV efficiency gains are due to the strategy for battery charging and discharging. Various levels of battery capacity yield no all-electric range (HEV-0),

capacity for a 20-mile all-electric range (HEV-20) and sufficient capacity for a 60-mile all-electric range (HEV-60). The operation of the HEV-20 and HEV-60 configurations differs from the HEV-0 in that the plug-in is charged overnight, and provides all-electric operation until the battery state-of-charge is reduced to 20 percent, at which point the engine must operate to maintain this minimum charge. At that point, it operates similarly to an HEV-0.

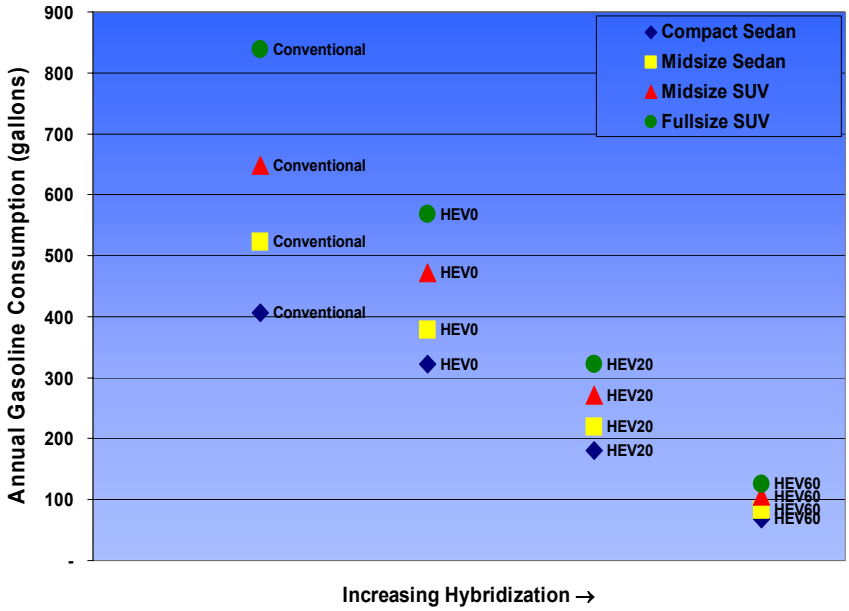
The bottom line for plug-in hybrid technology is shown in Figures 2-2 and 2-3. As the design is pushed to higher levels of all-electric range, the vehicle depends more on grid power as its energy source, and less on petroleum. The HEV-60 will cover some 90 percent of the typical Californian's driving cycle with zero emissions (tank to wheel), no loss in flexibility to take long trips, and at about half the cost per mile.

Sustainable mobility means among other things that the emissions over the entire chain, from the well to the use of fuels in vehicles, should be as low as possible. In this sense the GHG emissions emitted by electric power generation (grid) and life-cycle-analysis of vehicles have to be considered in the calculations.



Courtesy of Dr. Andrew Frank, University of California Davis

Figure 2-2. Greenhouse Gas Emissions (Tank to Wheel) for all Light-Duty Cars Trucks



Courtesy of Dr. Andrew Frank, University of California Davis

Figure 2-3. Annual Gasoline Consumption for 12,000 Miles of Driving for all L/D Vehicles

2.4 Stationary Applications

2.4.1 Stationary Fuel Cells [10]

The California Stationary Fuel Cell Collaborative [11] has taken a leadership role in facilitating the advancement, demonstration, and use of fuel cells for power generation in stationary applications throughout California. Members of the Collaborative represent organizations interested in combining efforts and resources towards commercialization of SFCs in California. Several California agencies such as the Air Resources Board, the California Energy Commission, the Department of General Services, the National Fuel Cell Research Center, and the South Coast AQMD form a Core Group of the Collaborative. The Core Group also includes non-government organizations and public utilities. In addition, members of the Collaborative include fuel cell manufacturers, fuel suppliers, research institutions, vehicle manufacturers, energy companies and other associated industries.

The Collaborative envisions stationary fuel cells serving critical, and economically viable, roles in support of hydrogen refueling infrastructure. Stationary fuel cells are already deployed in operating hydrogen-refueling stations, and their use throughout the hydrogen highway network can contribute to overall hydrogen highway success in several ways. Namely, stationary fuel cells can:

- Increase the efficiency and utility of the refueling process.
- Increase hydrogen utilization in stations that may otherwise be underutilized.
- Advance hydrogen-refueling technology.

Two applications are immediately appropriate for SFCs in support of the hydrogen-refueling infrastructure. First, SFCs will be used to co-produce power and heating/cooling at the refueling site. This can be accomplished through an independent energy station, an institutional facility (e.g., fleet refueling), or a commercial business building (e.g., convenient refueling for building occupants). While SFCs are conventionally fueled by natural gas, the natural gas is reformed within the system to produce hydrogen, which is consumed by the SFC to produce electricity and heat. The availability of hydrogen at a hydrogen-refueling site provides fuel that a SFC can consume directly. This provides not only a source of local electric and thermal power that is valuable, but supports the overall balance of plant and balance of operations and control of the refueling station. Without the SFC, the hydrogen production or storage on-site would be required to waste hydrogen (through venting or flaring), operate less efficiently, or shut down and restart regularly (leading to increased waste and lower efficiency) to match hydrogen refueling demands. The analogy is a hydroelectric dam, which, in addition to producing electricity, is storing water for domestic use and serving to control flooding. In the case of hydrogen refueling, the SFC serves to utilize the hydrogen stored onsite for the generation of electrical and thermal power when automobile refueling needs are low and/or hydrogen storage is reaching full capacity, conferring to the facility ample flexibility to meet both power thermal needs (which may include an on-site fuel processor) at overall efficiencies that approach 90 percent.

The second immediate application of SFCs to the hydrogen highway is their use to generate hydrogen on-site in order to meet the refueling requirements in parallel with the generation of electricity. This strategy utilizes the emerging high-temperature stationary fuel cells (HTFCs) such as molten carbonate fuel cells and solid oxide fuel cells. HTFCs possess four major characteristics that make them remarkably attractive for playing a synergistic role in the hydrogen-refueling plan for California led by Governor Arnold Schwarzenegger:

1. High fuel- to-electricity conversion efficiencies up to 50 percent (using natural gas or biogases such as landfill and digester gas),
2. High-quality waste heat sufficient for heating, industrial processing and thermally activated cooling applications,
3. Co-production of power and hydrogen with minor modifications of the current power-only products; and
4. Ultra low criteria pollutant emissions.

As with all fuel cells, HTFC systems do not use all the fuel that is supplied. The unconsumed fuel is traditionally oxidized at the exit of the stack and used in other parts of the system before being exhausted as high-quality waste heat. With modifications to the current HTFC power-only products, this unused fuel can be separated and used for cost-effective co-generation of hydrogen. This application is viewed as potentially the most efficient, cost-effective, and environmentally sensitive means of generation of hydrogen from natural gas. This claim is bolstered by several technical facts: (1) heat required by a natural gas reformer is synergistically provided exactly where it is needed by the heat release of the SFC electrochemical reactions, (2) fuel cell efficiency increases since the SFC is not required to consume as much hydrogen in a single pass through the fuel cell stack, (3) local production of hydrogen at the refueling station

avoids all costs and emissions associated with hydrogen transport (which are very significant), and (4) dynamic selection of relative hydrogen and electricity production levels provides the user with flexibility to maximize cost effectiveness over the entire and widely varying duty cycles associated with both refueling and electricity value. At central plant scale, thermodynamic analyses of HTFC configurations reveal that the co-generation of hydrogen and electric power will be the environmentally responsible strategy of choice in future natural gas and coal-fired applications.

Stationary fuel cells are emerging today into the commercial natural gas market around the world. Residential-sized units at 5 kilowatts, and commercial building and industrial units ranging from 200 kilowatts to multiple megawatts are being widely deployed. The pricing in the early market is understandably higher than conventional technologies, but incentive and buy-down programs are providing economically viable solutions today. In addition, the projections established by Collaborative surveys point to improved manufacturing and mass production that will bring down the base price of stationary products to competitive levels within a few years. The recovery and utilization of waste heat provided by the distributed generation paradigm is a key to a competitive economic strategy. Studies conducted by the Collaborative show that energy operating costs can be reduced by more than a factor of 2 through use of co-generating fuel cells (based on typical electric and natural gas utility rates in force today). The associated payback period can be attractive to both private and public investment.

The Hydrogen Highway Plan for California can and will benefit by the use of SFC technology and installations that use natural gas. In addition, SFCs that directly use hydrogen can provide electricity and co-generation benefits to a broader cross-section of California citizens using hydrogen that would have otherwise been wasted. SFC technology will be advanced through these deployments and the track record established by hydrogen highway installations will have a positive impact on the role of the SFC market. The high-efficiency of HTFCs, near- zero emission of criteria pollutants, and high quality of waste heat are directly supportive of both the spirit and mission of the Hydrogen Plan for California. The additional abilities of SFCs to (1) efficiently co-generate hydrogen in a remarkably environmentally responsible manner, and (2) stabilize the operations and controls of a hydrogen refueling plant are also directly applicable and needed for success of the Hydrogen Plan for California.

2.4.2 Stationary Hydrogen IC Engines

Internal combustion engines are in widespread use in a variety of stationary applications including pumping, distributed generation, standby power, or various motive power applications. Several companies are currently offering stationary ICEs designed to run on natural gas, hydrogen, or any combination of the two (i.e., HCNG). Collier/Daewoo and Cummins/Westport. both have currently available models which are modifications of long-established engine designs. Stuart Energy also has a hydrogen ICE generator (Ford V-10, 6.8L engine) option for their electrolyzer station, which can provide backup, peaking, or supplemental power.

2.5 Renewable Energy and Hybrid Hydrogen Systems [12]

Hybrid hydrogen system concepts include those that would combine a stationary fuel cell with a turbine generator for enhanced energy efficiency, and those that would combine hydrogen production with renewable energy systems. We consider true "hybrid" systems to be those that combine power *generation* from two different types of systems, so we reserve the term "hybrid" here for those types of systems but also include some discussion of systems that use renewable energy sources to produce hydrogen using electrolyzer technologies. Hybrid fuel cell / turbine systems are currently under development and nearing commercialization. Renewable energy / hydrogen systems have been demonstrated in a few locations and are undergoing further development.

With regard to hybrid stationary fuel cell / turbine systems, the schemes that are currently being explored would combine a high temperature fuel cell (solid oxide or molten carbonate) with a microturbine or other turbine generator by using excess anode "tail gas" from the fuel cell to operate the turbine generator. Electrical efficiencies of up to 60 percent (near term) and 70 to 75 percent (longer term) appear to be feasible from these hybrid system concepts, with overall thermal efficiencies of 80 percent or more possible with waste heat recovery.

Major fuel cell system developers and research centers are exploring this concept. Companies currently developing hybrid fuel cell systems include Siemens-Westinghouse (solid oxide fuel cell based), General Electric (solid oxide fuel cell based), and Fuel Cell Energy (molten carbonate fuel cell based). The National Fuel Cell Research Center is leading efforts to develop, design, demonstrate, and evaluate fuel cell hybrid technology. The general outcome of recent hybrid system demonstration projects appears to be that the hybrid fuel cell concept is technically feasible but faces challenges associated with the integration of a suitable turbine generator with the fuel cell power plant. Codes and standards compliance has also been raised as an additional challenge.

Siemens Westinghouse has been experimenting with a pressurized hybrid system based on a solid oxide fuel cell coupled with a microturbine generator, with a total power rating of 182 kWe. The experiments have been conducted as a partnership with Southern California Edison, the U.S. Department of Energy, the California Energy Commission, and the National Fuel Cell Research Center. The system has demonstrated an efficiency of 53 percent (LHV basis) and is being called the "world's most efficient natural gas powered fuel cell." The company is also experimenting with a somewhat larger pressurized hybrid system with its partner Edison S.p.A. in Italy. Siemens Westinghouse considers these demonstrations proof of the feasibility of the hybrid system concept, but indicates that further work is needed particularly with regard to developing a more suitable turbine generator and better integration of the two systems.

FuelCell Energy has experimented with a 250 kW molten carbonate fuel cell combined with a Capstone model 330 microturbine. Over 2,900 hours of hybrid system operation, electrical efficiency of about 52 percent has been demonstrated (LHV basis). FuelCell

Energy is now designing a multi-MW hybrid power plant and investigating suitable turbine technologies to incorporate into the system.

Renewable energy / hydrogen systems are currently being explored through several demonstration and operational projects. These typically employ solar or wind power to produce electricity that then is used to power an electrolyzer for hydrogen production. The hydrogen is then used to refuel prototype vehicles or in a stationary fuel cell system for electricity production.

Examples of recent renewable hydrogen projects (among several others) include:

- A wind-hydrogen project at Exhibition Place in Toronto, Canada with a Hydrogenics electrolyzer
- A wind-hydrogen project using a Stuart Electrolyzer in Palm Dessert sponsored by the South Coast AQMD
- A solar hydrogen project at the National Research Council building in Vancouver, Canada with a Hydrogenics electrolyzer
- The SunLine Transit facility in Palm Springs, California, where hydrogen is produced through solar-powered electrolysis to fuel hydrogen vehicles
- The Solar-Wasserstoff-Bayern hydrogen demonstration project at Neunburg Vorm Wald, Germany, where a 370 kW solar array is producing hydrogen for both fuel cell power and hydrogen vehicle refueling
- A solar hydrogen project at the Stuart Energy Systems headquarters in Toronto, Canada
- Stuart-Toyota-SIT PV-H2 Electrolyzer Vehicle Re-fueling Tent
- A solar hydrogen project in Trinidad, California developed by the Schatz Energy Research Center at Humboldt State, California
- A solar hydrogen experiment at the Instituto Nacional de Técnica Aeroespacial in Huelvo, Spain
- A solar hydrogen experiment in El Segundo, California sponsored by the South Coast AQMD and Clean Air Now.

2.6 Telecommunications/Broadband

For the telecom/broadband market, there are two scenarios where fuel cells are applicable:

- Scenario #1: The grid-tied telecom sites where direct-hydrogen fuel cells could be installed for back-up power
- Scenario #2: The off-grid sites where currently a solar/genset hybrid is installed. The solar system provides primary power and the genset operates as a backup to the PV system. Potentially, fuel cells could displace the genset as the back-up device

In Scenario #1, the fuel cells would likely be sized for 1 to 10 kW, and would operate 10 to 100 hours per year. These systems would be direct-hydrogen. Approximately 32,000 of these telecom and broadband sites exist in California. How many might be

converted to a fuel cell back-up device is unknown, but adoption will be related to economic and other incentives.

For Scenario #2, the fuel cell system would likely be sized for about 1 kW and would operate about 500 hours per year. There are about 1,000 to 2,000 of these sites in California. The sites are typically remote, and it is difficult to deliver hydrogen to them. Therefore, a reformer-based fuel cell system should be considered for Scenario #2.

Several companies are working on a product for Telecom/Broadband solution: Avista, Ballard, Hydrogenics, IdaTech, Plug Power, et al. Currently, industry is offering a 5 kWe system under controlled introduction strategies. These products are designed to serve the cable broadband, telecommunications, and uninterruptible power supply markets (industrial plant controls and other mission-critical applications). Pricing for 5 kW systems is $15,000 ($3,000 per kilowatt) [13]. Telecom is a near-term market for these products and industry is applying considerable resources. Future product offerings are expected to be 2 to 12 kWe output range [14]. Products are direct-hydrogen systems (no reformer) containing a PEM fuel cell, power electronics, and BOP (balance of plant) and are zero-emission. They are refueled by replenishing hydrogen cylinders. These systems are not continuously operated – they are intended to provide back-up power and displace batteries (valve regulated lead-acid and other). Expected system life is 500 cycles and 1,500 operating hours over a 10-year life. Societal benefits are perceived to be a reduction in batteries (environmental) and battery maintenance costs (fuel and labor to periodically maintain the batteries). Assuming that these systems were to operate for the entire 1,500-hour life, and assuming that 13 liters per minute of hydrogen are required per kilowatt of electric power, then over the lifetime of the system about 500 kg of hydrogen would be used. More likely, this system operating in Scenario #1 at 55 hours per year would require about 185 kg of hydrogen over the 10-year life.

Similar estimates can be made for a reformer-based fuel cell system operating in Scenario #2. Societal benefits of a reformer-based fuel cell system operating in this application are a reduction in gensets (environmental: emissions, noise, fuel spills). Additionally, if a renewable liquid fuel (bio-diesel, bio-methanol) were utilized, dependence on fossil fuels could be reduced. Since these sites are considered remote, and since this is not a direct-hydrogen application, the benefit to the hydrogen network is not direct. Indirectly, however, a reformer-based fuel cell system operating on bio-fuel creates demand for these renewable fuels; as the supply of these bio-fuels develops, the potential for producing hydrogen from these fuels for use in the hydrogen network can be realized. Industry is testing reformer-based fuel cell systems for grid-independent, remote telecom applications [15].

These systems are considered pre-commercial, with no reliable commercial launch date published. Considering the state of the technology, commercial product can be expected prior to 2010. Environmental hardening and economic factors are barriers to earlier adoption. Assuming 500 hour/year operation, 1 kWe average power required, and 13 liters of hydrogen per minute per kilowatt, each system would require 33 kg of hydrogen per year.

Long-term (2010 and beyond), fuel cell systems might provide primary power for telecom and broadband sites. However, fuel cell system cost, maintenance, and reliability improvements will be required before such adoption occurs on a widespread basis (will need to compete directly with grid power). When this occurs, these primary power fuel cell systems will either require a network of hydrogen circuits (piping systems) to supply hydrogen to direct-hydrogen fuel cell systems, or fuel (such as bio-methanol, bio-diesel, bio-methane, or fossil fuels such as natural gas or propane) will need to be supplied to reformer-based systems. Assuming continuous operation (8,760 hours/year), 5 kWe average power required, and 13 liters of per minute per kilowatt, each system would require 2,900 kg of hydrogen per year.

Representative fuel cell applications in the telecom / broadband market are presented in Table 2-3.

The references contain links to additional information on a variety of stationary applications [16].

Table 2-3. Telecom / Broadband Applications

Application	Technology	Availability	Power Rating	Fuel Source	Fuel Specification	Operating Hours / year	H_2 Consumption	Number of Sites in CA	Other
Grid-Connected	PEM, Back-up mode	2004	5 – 10 kWe	Bottled H_2	H_2 >99.95% CO <1 ppm	10 – 100	18.5 kg/year per system	~32,000	Pre-commercial available in 2004, commercial in 2005
Grid-Connected	PEM, Back-up mode	Requires H_2 piping infrastructure	5 – 10 kWe	Piped H_2	H_2 >99.95% CO <1 ppm	10 – 100	18.5 kg/year per system	~32,000	Could convert from bottles to piped H_2
Prime Power	PEM, Prime Power	Beyond 2010	5 – 10 kWe	Liquid Fuel with Reformer	MeOh Diesel (low S)	8,760	2,900 kg/year per system	32,000	Economic & reliability factors must be competitive with grid power
Grid-Independent	PV / PEM Fuel Cell Hybrid	Before 2010	1 kWe	Liquid Fuel with Reformer	MeOh Diesel (low S)	500	33 kg/year per system	1,000 – 2,000	Most sites remote, i.e., no H_2 delivery, no piped fuel. Best is Liquid MeOh / low sulfur diesel; LPG possible.

2.6.1 Refueling Stations

2.6.1.1 Dedicated Compressed Natural Gas (CNG) and Hydrogen Refueling Stations

Among the serious risks facing dedicated stations, and for the public agencies and private investors who fund them, is the real issue of stranded investments. Combining alternative technologies, such as natural gas and hydrogen, in a facility can potentially reduce this risk.

For some manufacturers compressed direct hydrogen seems to be the dominant fuel choice for early hydrogen vehicles. Announcements of major automobile manufacturers, including Ford, Toyota, Honda, Volkswagen, Hyundai, indicate at least in the early years, that compressed hydrogen could be the fuel choice at least for demonstration purposes. Other manufacturers such as BMW and GM are working with liquid hydrogen as well. Solid metal hydride storage is now appearing on vehicles (Ovonics). Therefore, dedicated hydrogen refueling stations, dispensing compressed or liquid hydrogen, could also face stranded investment risk from several competitive storage technology developments including liquefied hydrogen and metal and chemical hydrides.

2.6.1.2 Compatible Hydrogen-CNG Stations

Installing two dedicated refueling stations – one for natural gas vehicles (NGVs) and other for FCVs — entails the serious risk of stranded capacity, and stranded investment. Besides, significant additional land and additional budgets may be needed to operate two networks in parallel, which in turn may discourage large scale installations of FCV refueling stations.

Potentially, the CNG infrastructure for NGV refueling could be an introduction for future hydrogen infrastructure. In some cases, it is practical to install compressors capable of compressing both. This novel approach could significantly reduce the cost of a dedicated single fuel infrastructure by not duplicating equipment, nor requiring as much additional land. It would also reduce the potential of stranded costs by utilizing the refueling station now for CNG vehicles, instead of sitting idle until the demand for hydrogen powered vehicles increases.

It should be noted that this way just compressed hydrogen can be refueled in vehicles. For the vehicle supplied with liquid hydrogen the fuel has to be delivered by truck to the stations. There are systems currently in development and testing that would use liquid hydrogen as the source of both liquid and compressed supplies, also adding CNG to the pump selections, thereby addressing this problem.

The addition of hydrogen fueling capability to an existing CNG site is immediately less capital intensive if the same footprint can be used for hydrogen. Since these properties are already being used to fuel CNG, virtually all the site improvements needed for hydrogen fueling, paving, lighting, drainage and fuel islands are already available [17].

At least two companies are developing, and one is offering for sale, such a system. While this technology is in the early commercialization stage (no commercial units yet in operation), it seems to address the issue of utilizing expensive components for both CNG and hydrogen, thereby reducing the potential for stranded cost. In this hydrogen-CNG hybrid fueling station, hydrogen is delivered by a trailer, which may be the most economic method for hydrogen delivery in the near term. This takes advantage of the economies of scale for commercial production of hydrogen and requires less investment in the station.

The strategy for such a system relies on introducing hydrogen at the last stage of compression to displace CNG. A purge cycle would also be required with sufficient purity to guard against stack contamination and enable fuel cell vehicle use. Until this long-term purity issue can be resolved, the co-dispensing of CNG and hydrogen may initially only be applicable for hydrogen ICE or HCNG vehicles. The potential capital savings for such systems, however, offers promise and should continue to be evaluated. Future stations that are already designed and built to be converted to hydrogen in the future will have a lower cost to add the hydrogen capability. Hydrogen refueling stations retrofitted to CNG stations built by different companies will cost considerably more.

Refueling equipment manufacturers have expressed a willingness to provide the capital resources to make these CNG-to-hydrogen station upgrades, in exchange for a commitment to purchase a specified amount of CNG. To the extent that the resident fleet at that station was going to buy a quantity of CNG in any event, the resulting revenue stream creates an opportunity to finance the hydrogen refueling network without out-of-pocket expenses.

2.6.1.3 Portable Refueling Stations

A near-term, economical solution to providing hydrogen for vehicle fueling is the concept of portable refueling stations. Air Products and Chemicals has developed the HF-150 mobile hydrogen fueler. It supplies H_2 to a limited number of vehicles, which may be appropriate for jump-starting the infrastructure. SCAQMD has selected this technology for use at some of its hydrogen fueling stations. An advantage of the mobile refueler is that it can be towed from one station to another in the event that the vehicle demand was not predicted accurately. The reduced risk of stranded investment may be worth a slightly higher price of hydrogen supplied from tank trucks that must replenish the supply [18].

2.6.1.4 Home Refueling Stations

Stuart Energy Systems, Inc. is developing an electrolyzer system for use in the home, to refuel a vehicle using less-expensive, off-peak power. While this product still faces cost challenges, the concept is potentially disruptive, in that it leapfrogs the need for a regional refueling infrastructure. The development timeline for this device is unknown at this time.

2.7 Fuels Applications

2.7.1 Hydrogen/Natural Gas Blend (HNG) Fueled Vehicles

One of the biggest challenges facing the Hydrogen Highway is finding early markets for hydrogen as a vehicle fuel. With fuel cell vehicles still many years away from mass production, it will be difficult for the private sector to justify investment in the fueling infrastructure that will help promote the commercialization of hydrogen in transportation. Also, without early markets for hydrogen, prices for the fuel will remain high, erecting a substantial barrier to the development of the Hydrogen Highway.

Yet, California has already invested heavily in the development of an alternative fuel-dispensing infrastructure that not only holds lessons for future hydrogen development, but could also serve as a springboard for the Hydrogen Highway. There are several thousand natural gas vehicles in California, and several hundred fueling stations scattered around the state, particularly along the north-south transportation corridors. Even more important, most of these vehicles are heavy-duty trucks and buses, which consume prodigious volumes of fuel compared to their light duty cousins. If these vehicles could be modified to burn a combination of natural gas and hydrogen, they may serve to provide the demand necessary to kick-start the industry.

The societal benefits of hydrogen/compressed natural gas blends (HCNG) vehicles are substantial. First, since compressed and liquefied natural gas vehicles (CNG, LNG) vehicles and fueling stations are already deployed, the state could spur both hydrogen production and dispensing infrastructure without the costly investment in new stations and new vehicles. Second, as was demonstrated by Sunline Transit, adding hydrogen to a natural gas vehicle significantly reduces the production of NO_x. A 20 percent by volume mix of hydrogen with natural gas reduces NO_x emissions by as much as 50 percent [19]. Third, by adding renewably produced hydrogen to the fuel, it helps reduce the nation's dependence of foreign sources of energy. Although an 80/20 mix of natural gas and hydrogen only displaces about 7 percent of the natural gas energy content, this is still 7 percent less imported fuel.

The cost of the initial technologies will be substantial, but only until they can be demonstrated. One challenge will be the development of on-board blending technology for LNG heavy-duty vehicles. Since LNG is the fuel of choice for most natural gas vehicles that travel the corridors that connect the state's cities and California to the rest of the country, in order to get hydrogen used in this application it would be necessary to enable these vehicles to utilize hydrogen/natural gas blends. Since on-board blending does not exist, this hurdle must be overcome to develop this application.

The barriers to hydrogen/natural gas blends are significant. At this time, there are few manufacturers who build engines that come off the assembly line capable of burning natural gas and hydrogen simultaneously. Only two companies, Cummins/Westport, and Collier/Daewoo, have experience calibrating their stationary natural gas engines to run on blends.

The technology for hydrogen/natural gas blends mostly exists, and some demonstration projects have been completed. The rollout of vehicles will likely take the rest of this decade. Demonstration projects should begin in 2005 and be complete in 2006. The rest of the decade can be used to convert existing units to HNG capabilities, as well as enabling all new natural gas engines to run on a hydrogen-natural gas mixture.

2.8 Portable/Consumer Applications

2.8.1 Airport Ground Support Equipment (GSE)

Airports provide many opportunities for implementation of hydrogen applications:

- Generators
- Tool/lighting/maintenance carts
- Trucks (fueling, galley supply, cabin cleaning, and fire)
- Tow tugs
- Passenger stairs
- General access lifts
- Baggage tractors
- Cargo loaders (belt loaders)
- Buses and other personnel carriers
- Aircraft APUs (Auxiliary Power Units) to provide power for electricity for flight systems and hotel loads (heating, cooling, lighting, and food service) while the aircraft is on the ground.

There are several sizes/classes of GSE (aircraft ground support equipment) for each of the above applications.

There are different scenarios for implementation of hydrogen in these applications:

1. Fuel cells and hydrogen ICEs could be designed and implemented for the specific application (fire truck, tow tug, etc.)

2. Fuel cells and hydrogen ICEs could be designed and implemented as “universal power modules” that are applicable and interchangeable to more than one specific application

3. Fuel cells and hydrogen ICEs could be integrated with on-board reformers

4. Fuel cells and hydrogen ICEs could be implemented with hydrogen storage (compressed, liquid, metal hydride, etc.)

5. More than one centralized reformer (operating on diesel, JP-8, natural gas, or methanol) for generating hydrogen could be located at each airport

6. Vehicles/GSE could be battery-powered electric where the electricity for recharging is generated from centralized fuel cells providing power to recharging stations

Eventually, aircraft may contain fuel cell APUs for starting the main engines and providing heat, power, and water (hotel loads) for the aircraft. These APUs would also enable the development of a more electric aircraft. Although this aircraft APU is not considered GSE, it would displace GSE and reduce pollution levels while the aircraft is requiring power on the ground.

Generally, the quantities of the GSE are relatively low, and the cost associated with development of fuel cell systems specialized for a specific type of GSE is perceived to be relatively high. Therefore, perhaps the best model for implementation of fuel cells for GSE is the universal power module approach (#2, above) so as to increase quantities and drive down costs. This approach has been considered by the U.S. Air force. For PEM type fuel cells in these applications, the fuel specification is hydrogen purity greater than 99.95 percent with less than 1 ppm carbon monoxide. Early pre-commercial equipment and test programs are underway for several of the GSE. Drive trains for all-electric GSE equipment are commercially available and robust, but power for these vehicles is currently supplied by batteries rather than fuel cells. It is anticipated that airport flight line operations will accept hydrogen as a fuel. Table 2-4 shows GSE hydrogen consumption based on 1995 and later data from California ARB and other sources.

2.8.2 APUs: Truck Stops

Reduction of truck diesel engine idling is desired for environmental, health, and economic reasons. At some travel centers, TSE (truck stop electrification) has been implemented. These travel centers provide individual truck stations with heating, cooling, AC power, telephone, internet, and other services (e.g., IdleAire, LLC).

These systems currently operate from grid power. Conversion to fuel cell power will not occur until cost of the fuel cell systems is lower, and reliability is higher, or unless grid power is unavailable. With the CA PUC Self Generation Incentive Program, grid competitive fuel cell power can be provided to these truck stops. With a high temperature fuel cell like a Molten Carbonate Fuel Cell (MCFC) providing tail gas hydrogen as a byproduct (useful for vehicle refueling), this becomes a very cost effective solution.

Nationally, there are an estimated 272,000 commercial travel center parking spaces with an estimated occupancy of 66 percent (IdleAire). Assuming that TSE was universally implemented and utilized by truckers, all power was provided by low temperature fuel cells, and that the power demand at each space is 1 kW, and 13 liters per minute of hydrogen is required per kW, the nationwide demand for hydrogen for this application would be 1.226×10^9 cubic meters per year, or 104×10^6 kg/year. The actual percentage of this demand within California depends on truck traffic volume, climate, and other factors. This demand is unlikely to be realized until after 2010, since fuel cells are currently unable to compete with grid power.

Table 2-4. Aircraft Ground Support Equipment Hydrogen Requirement Estimates for California [20]

Equipment	Diesel	Gasoline	LPG & CNG	Statewide Total	Power, HP	kW	Load Factor	Annual Hours	H_2, liters/yr	H_2, m^3/yr	H_2, kg/yr	Availability
Baggage tug	440	646	89	1175	100	75	0.55	876	$32.9x10^9$	$32.9x10^6$	$2.8x10^6$	Pre-commercial testing
Belt loader	172	304	19	495	60	45	0.50	810	$7.0x10^9$	$7.0x10^6$	$595.6x10^3$	
Forklifts, lifts, & cargo loaders	197	319	214	730	70	52	0.50	719	$10.7x10^9$	$10.7x10^6$	$909.7x10^3$	
Ground power unit	228	71	0	299	150	112	0.75	796	$15.6x10^9$	$15.6x10^6$	$1.3x10^6$	Pre-commercial stationary generators available
Aircraft tug, Wide Body				55	500	373	0.80	515	$6.6x10^9$	$6.6x10^6$	$559.0x10^3$	
Aircraft tug, Narrow Body				219	130	97	0.80	551	$7.3x10^9$	$7.3x10^6$	$622.0x10^3$	Pre-commercial tugs available
Airstart unit	70	0	0	70		0	0.50		0	0	0	
Air conditioner	22	0	0	22		0	0.50		0	0	0	
Deicer	0	29	0	29		0	0.50		0	0	0	
Cart & lavatory cart	0	22	0	22		50	0.50	550	$236.0x10^6$	$236.0x10^3$	$20.1x10^3$	
Fuel trucks	23	56	26	105		300	0.50	550	$6.8x10^9$	$6.8x10^6$	$575.0x10^3$	
Utility trucks	20	356	31	407		160	0.50	600	$15.2x10^9$	$15.2x10^6$	$1.3x10^6$	Pre-commercial step-vans available
Bobtail	0	92	2	94		0	0.50		0	0	0	
Other	17	160	17	194		0	0.50		0	0	0	
	1403	2115	398	4190		0	0.50		0	0	0	
										Total =	$8.7x10^6$	
Buses						200						Pre-commercial units available now
Aircraft APU						300-1000						Estimated availability of first commercial units after 2010

Data from various sources including California Air Resources Board (1995 data).

Fuel cells are a potential solution for off-grid truck stops (e.g., remote rest areas). Conceivably, the cogeneration aspects of fuel cells could also be put to use. Economics of this scenario could be favorable prior to 2010, assuming there is demand for off-grid electric services at truck stops. Hydrogen could be supplied in gaseous form, or a reformer could be installed on-site to generate the hydrogen. For reformer-based systems, natural gas, LPG, or liquid fuel (e.g., methanol, low sulfur diesel) would need to be delivered to these remote truck stops.

2.8.3 Small Consumer Products

Power sources for cellular phones and other portable products such as laptop computers, radios, and just about anything else currently powered by batteries are being developed. Familiar names such as Nokia, Casio, Motorola, NEC, Toshiba, and Samsung among others are actively developing small fuel cells. These devices will promote public awareness of fuel cell technology and increase general familiarity and comfort level with hydrogen fuel and fuel cells. This increased experience with handling hydrogen may indirectly promote public adoption of other hydrogen fueled devices (fuel cell vehicles, generators, etc.) that might be fueled directly from hydrogen, thus increasing demand for hydrogen and hydrogen storage devices.

Various consumer products could potentially become other markets for hydrogen as the clean-burning feature of hydrogen is desirable from an air pollution perspective. By appealing to the purchaser of “green” products, a consumer product, used here to represent a body of unexpected product developments, could help develop the market for hydrogen since neither the purchase of the product nor the fuel will be dependent on the unit price of hydrogen, given that very small quantities will be required. The hydrogen station would provide refilling services for either bottled or chemical stored hydrogen with consumers trading in empty containers in exchange for filled containers, similar to current propane service for barbeques.

While these products would not contribute significantly to the overall throughput of hydrogen, hence would not have significant contribution to lowering the cost of production of hydrogen, there would be other equally important benefits. First through widespread consumer use of hydrogen fueled products, consumers would become familiar, and comfortable with the use of hydrogen in everyday applications. This will override the persistent fears about safety stemming from old urban legend about early hydrogen experience, which popular press continues to exploit for eye-catching headlines. Secondly, small consumer products will help develop supply and distribution channels for hydrogen fuel with tendrils far more intricate and numerous than the larger supply channels for bulk fuel. This will be instrumental in the development of a robust market for hydrogen fuel.

The references contain website with further information on small fuel cell product development [21].

2.9 Hydrogen Storage Systems

While storage is not an “application” per se, hydrogen storage is a challenge for nearly all applications. Because of its physical and chemical properties, hydrogen storage systems tend to be large, heavy, and expensive (e.g., compared to gasoline fuel tanks with equivalent energy contents). The National Research Council Hydrogen Study [22] identified hydrogen storage technology improvements as a high-priority R&D requirement, and storage is in fact a key element of the DOE Hydrogen Fuel Cells and Infrastructure Technology (HFCIT) program [23].

Conventional methods for storing hydrogen involve increasing its density through compression (with storage in high-pressure vessels) or liquefaction (with storage in insulated cryogenic vessels). Compressed and liquid hydrogen storage is discussed in more detail below.

2.9.1 DOE Programs

More advanced methods involve storing molecular or atomic hydrogen in other materials. A growing number of private-sector companies are already developing, demonstrating, and commercializing proprietary solid Metal Hydride storage technologies. The DOE HFCIT program is supporting R&D in three areas:

- Adsorbed Hydrogen
- Hydrides
- Chemical Hydrogen Storage

Carbon is the most commonly used material for hydrogen adsorption, and vigorous research is underway to develop carbon nanostructures that provide a high hydrogen storage capacity. Hydrogen storage in simple and complex metal hydrides has been studied. Recent R&D has focused on a class of complex metal hydrides that includes alanates, which have a high hydrogen capacity (e.g., weight %) and release substantial quantities of hydrogen when warmed to modest temperatures. Chemical hydrogen storage involves hydrogen-generation reactions that are not easily reversed. Hydrogen-storing liquids such as sodium borohydrides are the subject of active R&D. From a physical chemistry perspective, the distinction between complex hydrides and chemical storage can be quite subtle.

DOE has budgeted approximately $100 million for hydrogen storage R&D over the next five years under their “Grand Challenge” program [24]. This program sets aggressive performance progress goals for advanced hydrogen storage systems. Key goals include reducing the mass, volume, and cost required to store a given quantity of hydrogen. The DOE gravimetric and volumetric energy density goals (weight and size, which are characterized as kWh/kg and kWh/l, respectively) for 2005, 2010, and 2015 are shown in Figure 2-4. These goals are based on DOE’s estimate of what will be required for commercial viability rather than what can be expected from candidate technologies. Figure 2-4 also shows the current technology status for various hydrogen storage options, as defined by DOE. Table 2-5 lists DOE’s estimates of current hydrogen system costs and their future cost goals. It should be noted that some experts dispute

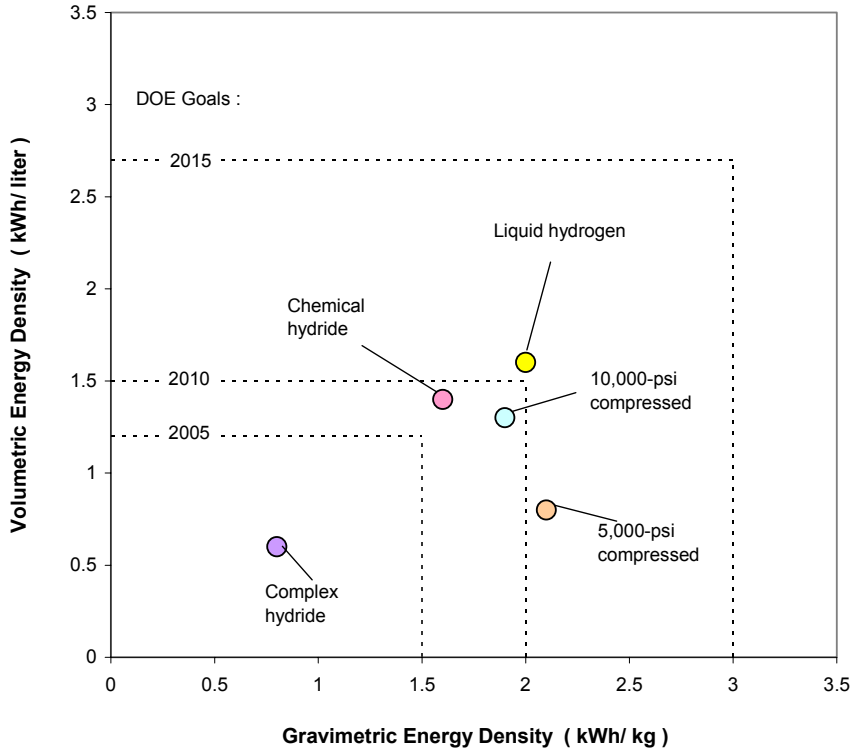


Figure 2-4. DOE's Estimates of Current Hydrogen Storage Systems Gravimetric and Volumetric Energy Density Compared with Future Goals

Table 2-5. DOE's Estimates of Current Hydrogen Storage Costs Compared with Future Goals

		Cost ($/kWh)
Current technology	Chemical hydride	8
	Complex hydride	16
	Liquid hydrogen	6
	5,000-psi gas	12
	10,000-psi gas	16
Future goals	2005	6
	2010	4
	2015	2

DOE's characterization of current storage technology capabilities as well as their selection of future goals.

The key characteristics and developmental status of the five primary hydrogen storage technologies are briefly summarized in the following sections.

2.9.2 Compressed Hydrogen Storage

Compressed hydrogen storage technology builds on decades of compressed natural gas (CNG) vehicle experience. While CNG is usually stored at 3,000 psi or 3,600 psi, compressed hydrogen storage technology is focusing on 3,600 psi and 5,000 psi (which are well developed and demonstrated), and 10,000 psi (which is the subject of intense development and testing).

Higher-pressure hydrogen storage is being pursued in an effort to increase the mass and energy of hydrogen that can be contained in a hydrogen fuel tank with a given size and weight. For example, 10,000 psi hydrogen has about 15 percent of gasoline's energy density, while 3600 psi hydrogen has about 7 percent.

A challenge affecting 10,000-psi hydrogen storage is the fact that, due to heat-of-compression effects, a tank that is rapidly filled to 10,000 psi will settle to roughly 7,000 psi after it cools down. Technologies being developed to provide a "full fill" include tank data monitoring during refueling, refrigeration of the dispensed gas, and special tank designs. Compressed hydrogen fuel tanks are generally cylinder-shaped, but research is underway to develop conformal-shaped tanks that fit better in available vehicle spaces.

Compressed gaseous hydrogen is currently the most commonly used storage mode for hydrogen fueled vehicles. Nearly all automobile manufacturers are experimenting with fuel cell vehicles equipped with compressed hydrogen fuel tanks. However, most manufacturers have been circumspect with regard to the commercial viability of vehicles with compressed hydrogen storage.

2.9.3 Liquid Hydrogen Storage Systems

The density of liquid hydrogen stored at near-atmospheric pressures provides about 25 percent of gasoline's energy density. The high density of liquid hydrogen is the main reason that this storage mode is used in hydrogen fueled rockets. Hydrogen liquefaction is an energy-intensive cryogenic refrigeration process that involves chilling hydrogen gas to approximately -420°F and then condensing the cold vapor to a liquid state. Liquid hydrogen is stored in vacuum-insulated tanks that minimize heat leaks and the resulting product venting.

Experimental hydrogen fueled vehicles in the U.S. as early as 1971 utilized liquid hydrogen fuel tanks [25]. There has been considerable work in Germany from the 1980s through the present to develop and test liquid hydrogen fueled vehicles, many of which are powered by ICEs rather than fuel cells. Liquid hydrogen fuel tanks are similar to liquefied natural gas (LNG) fuel tanks, which are being used successfully on

thousands of LNG vehicles. However, hydrogen's properties make liquid hydrogen tank design much more challenging than LNG tank design.

The safety and economic implications of hydrogen venting from vehicle fuel tanks if the vehicle is not in use is an obvious concern. Technologies being developed to address this problem includes tanks that utilize liquid air (which is produced in a heat exchanger when liquid hydrogen is withdrawn to the engine) to reduce heat leaks to the liquid hydrogen. Other liquid hydrogen storage innovations include systems that recover some of the liquefaction energy to power vehicle auxiliary equipment.

2.9.4 Metal Hydride Storage Technology

Metal hydride storage technology is based on reversible chemical reactions between hydrogen and certain metal alloys. Hydrogen is introduced, absorbed, and stably chemically bonded to the alloy, forming the metal hydride. The reversibility factor allows for storage of hydrogen ("charging"), and subsequent use of the stored hydrogen as a fuel ("discharging").

Charging the alloy with hydrogen results in "hydriding" and therefore storage. Heat is also released, and must be dealt with. Conversely, heat is used to "discharge" the metal hydride ("de-hydriding"), thereby releasing the hydrogen for application.

To achieve fast refueling for on-board vehicle storage applications, metal hydride systems require an efficient heat exchanger, to quickly remove heat generated during the "charging" process. Normal engine or fuel cell waste heat is quite sufficient for the discharge / dehydriding function. An example of an efficient, integrated system is seen on the Ovonic hydrogen-ICE-HEV (Prius).

Metal hydrides display moderately high volumetric storage densities, but relatively low gravimetric energy densities (see Figure 2-4). These storage densities are achieved at relatively low pressures, typically ranging from a few psig to several hundred psig at ambient temperatures. Since neither compression nor cryogenic cooling is required, metal hydrides offer one of the most energy efficient means of storing hydrogen.

Metal hydride storage systems can be tailored to fit the temperature and pressure requirements of particular applications, by changing the composition of the alloy, through materials design and engineering.

The nature of the metal hydride reaction also leads to enhanced safety, especially in the event of container damage. Because of the temperature-pressure relationships, only a small portion of the absorbed, stored hydrogen is released spontaneously in a container breech.

Metal hydrides can also be used to achieve safe and effective distribution of bulk hydrogen. Alloys that require higher temperatures to release hydrogen allow the hydrogen to be stored in a solid form, with minimal containment, and transported by common carrier means. Under ambient conditions, hydrogen stays chemically bonded to the host alloy matrix and remains in the solid form.

Ovonics has already obtained DOT exemption for shipping portable-application sized fully charged metal hydride canisters by common carrier.

2.9.4.1 Development Status / Industry Readiness

Portable storage canisters are currently furthest along the commercialization path and have been designed into a number of small fuel cell products that are currently in beta trials, and expected to be introduced to the marketplace in a matter of months.

Metal Hydride storage is already being successfully demonstrated in a number of H2-ICE-HEV vehicles

Stationary systems have passed through laboratory testing and are expected to be installed in field projects in the coming months.

2.10 Overall Findings

Table 2-6 indicates the overall findings of the analysis, giving details about products for each application.

Table 2-6 is the heart of this document, giving results of the review of the societal benefits, cost, availability, timing, challenges faced, opportunities, and any special needs for hydrogen quality of the various product categories examined.

Table 2-6. Hydrogen End Use Applications

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
Vehicles	Fuel Cell	High (ZEV) Criteria Pol. High (ZEV) CO_2 (depending on H_2 source) Efficiency – more efficient than other mobile H_2 applications, & roughly equivalent to current Prius (HEV). Energy Security – No near to mid-term benefits. Long-term benefits dependent on breakthroughs in storage and H_2 generation/distribution	High $xM High$xxk - Medium $xxk	Availability: currently, Prototypes, limited production. Challenges: Low range, lack of H_2 codes & standards, technology cost, incompatible dispensing interfaces, difficult insurance and liability environment. No or very limited customer demand based on likely price/performance. uncertain technology. No near term solution identified. Opportunities: LDV Fleets (probably limited to them through 2015 worldwide) Timing: Long term	High purity (> 99.999%)
	Transit buses- Fuel cell/electric hybrid	High- ZEV replaces high NO_x and PM diesels, bus visibility raises public awareness	High ~3M ea.	Available for Demonstration. Barriers: Cost and reliability for revenue service Readiness: >5 now 5-20 by 2010	
	Transit buses- ICE/electric hybrid bus	High- ZEV replaces high NO_x and PM diesels, bus visibility raises public awareness	Medium ~$800K ea.	Available for Demonstration. Challenges: Cost and reliability in revenue service Readiness: 0 now 0-20 by 2010	
	HCNG Vehicles	High – enables existing NG infrastructure and corridor-traveling NGVs to be used for H_2 development. May provide for majority of H_2 use during first decade of H_2 corridor development). Will provide significant NO_x reductions	Med $xxk on vehicles and stations. Incremental cost of vehicles may diminish past 2010 as conventional heavy duty engine costs escalate	No OEM manufacturing, with only one company actively developing HCNG capability in its NG engines. Requires modification to existing NG engines; uncertain whether all NG engines can be modified; may require retrofit of existing NG dispensing tech; performance and range losses. Readiness: Near-term for HDV and LDV Challenge: incompatible dispensing interfaces	Need on-board mixing capability for LNG vehicles; leverage CNG; proven to work in 20% H_2 mixes

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	Hydrogen ICE and Hydrogen ICE-HEV	-High (AT-PZEV) for pollutants and CO_2 (depending on H_2 source) AT-PZEV (silver) ARB category	High; Medium; Low (?) H_2 Car Co. $35K-77K for various 2005 models	Near commercial – H_2 Car Co. taking orders for 2005. Challenges include compliance demonstration with emerging safety standards and lack of H_2 infrastructure, incompatible dispensing interfaces. Opportunities include here-and-now transition pathway to H_2; Opportunities: no stranded ICE manufacturing infrastructure; no radical new technology – for users or maintenance.	
	Plug-in hybrids very high performance[a]	High: achieves transportation energy independence & security: liquid hydrocarbon fuels consumption reduced by up to 90% (HEV60) – run on ethanol or hydrogen and zero gasoline is used; appropriate for all primary vehicle applications; emissions and GHG much better than even benchmark HEV: ½ CO_2, <1/2 emissions. Enables V2G for DG power; dual-fuel allows independence if 1 fuel is catastrophically unavailable.	Low; affordable now: without incentives: initial purchase costs within existing price ranges of CV-ICE models and lines – only 17% more than conventional HEV; these costs will come down even more with volume battery production; Life-cycle costs on parity or lower than CV-ICE.	Barriers: U.S. OEM's have been reluctant. Availability: Here-and-now, conventional technology; Can run on nearly any liquid or gaseous hydrocarbon fuel (gasoline, ethanol, diesel, GNG, Hydrogen, etc). Half-dozen U.S. demonstration prototype vehicles already produced at UC Davis (Dr. Andy Frank); Daimler-Chrysler in alpha pilot, may produce Sprinter Van in volume; European manufacturers in demonstration and limited production; U.S. military supporting; Various OEM's and Tier 1 suppliers known to or rumored to have PHEV R&D&D programs.	Can run on hydrogen (but will use up to 90% *less*; can plug-in FCVs, H_2-ICEs, H_2-ICE-HEVs
	HD hauling vehicles – both Fuel Cell and H2-ICE	In addition to safety and run-time benefits, increased weight of metal hydride storage assists with counter- balance and traction	Fuel cell power systems for lift trucks appear cost-competitive with batteries in near term on life cycle basis.	A number of companies have announced plans to commercialize fuel cell powered material handling equipment in 2005. Beta testing of FC powered industrial trucks currently underway	
	Offroad vehicles-forklifts	High	10X; 1.5X; 1X	Available for demonstration. A number of companies have announced plans to commercialize fuel cell powered forklifts in 2005. Challenge: Cost Readiness: 2007	

[a] Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options," R. Graham Project Manager, July 2001

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	Offroad vehicles-Commercial Work Vehicles – both Fuel Cell and H2-ICE	High-Emissions reductions offer significant heath benefits– particularly in confined areas	10X; 1.5X; 1X	Available for demonstration. Several demonstration projects like the John Deere Gator utility vehicle are underway – particular interest in underground mining vehicles where diesel emissions present a significant health risk. Challenge: Cost Readiness: Before most autos	
	Offroad vehicles-NEVs	High –	10X; 1.5X; 1X	Available for demonstration. Challenge: Cost	
	Marine vehicles (low kW-recreational)	High - It has been claimed that marine applications create significantly more pollution than the LDV sector – hydrogen fuel could reduce this problem. Metal hydride storage vessels in the hull can provide ballast assist	2X; 1.5X; 1X Cost of fuel cell power supplies will drop significantly with increased commercial volume	Challenge: range, cost. Several projects have shown the benefits of fuel cells in marine vehicles, but with no policies in place to actively reduce marine emissions, there is little incentive for market adoption Readiness: Demos in 2005	Hydrogen requirements will depend on the specific application. Existing Coast Guard regs do not favor / allow compressed / liquid H_2 on board.
	On-Board Truck APUs	Reduced pollution, reduced engine wear, reduced fuel costs, quieter truck cab		Hydrogen supply, transportation, and refill infrastructure barriers. Exchangeable portable canisters could provide a solution; Trucking industry resistant to dual fuels.	

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
Stationary Fuel Cells - Hydrogen Refueling Stations[b]	Molten Carbonate Fuel Cell – high temperature – (DG)[c] used in: (1) Station load leveling via continuous power utilizing hydrogen from excess over refueling production (2) Co-Production of Hydrogen	High (near zero emissions, high efficiency, high value waste heat, potential H_2 co-production)	(1) 4500/2500/ 2000 (2) $3/kg for 250 kW unit, serving 25 cars/day, for 1000 kW unit 2.2 $/kg and 100 cars per day competitive	Availability: Commercially available now Now- with product refinement and increased manufacturing volume or Increased volume through Federal and/or State development contract	FCV PEM Spec
	Phosphoric Acid FC – Low Temperature (DG) – used in: Station load leveling via continuous power utilizing hydrogen from excess over refueling production	Medium-High (near zero emissions, medium high efficiency and waste heat value)	4,500/3,000/NA	Commercially available now	
	Solid Oxide FC– High Temperature (DG) – used in: (1) Station load leveling via power utilizing hydrogen from excess over refueling production (2) Co-Production of Hydrogen (3) Home Refueling	High (near zero emissions, high efficiency, high value waste heat, potential H_2 co-production)	(1) NA/4,000/ 2,000 (2) $3/kg for 250 kW unit, serving 25 cars/day, for 1,000 kW unit 2.2 $/kg and 100 cars per day competitive	Demonstrations and pre-commercial now/high cost, low volume, parts count are present challenges/SECA & environmental issues are main opportunities Availability: (1) Pre-commercial in 2007 (2) Commercially available in 2010, widespread with SECA technology after 2012	(2) FCV PEM Spec

[b] Hydrogen Refueling Stations. Stations designed specifically for the provision of hydrogen for vehicle refueling. DG in this application would in general operate on hydrogen and serve for balance of plant load leveling and, depending on the DG, meet refueling system electrical supply needs, serve for back-up power and peaking power. Some DG technologies (e.g., high-temperature fuel cells) could operate on natural gas and co-produce (on demand) the hydrogen required for refueling.

[c] Distributed Generation: In the context of the Hydrogen Highway Initiative, Distributed Generation can refer to either the "Distributed Generation of Hydrogen" or the "Distributed Generation of Power." In this table, DG refers to the "Distributed Generation of Power" that can support the Hydrogen Highway Initiative at either hydrogen refueling stations or energy stations. Note: There is no general agreement on a definition for the distributed generation (DG) of power. For the purposes of this table, DG is defined as "The generation of power at the location where a substantial fraction is used. In general, DG is in the power range from a few kilowatts to 50 megawatts."

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	Solid Oxide FC – High Temperature (Central Power - ~300 MW) – used in: Advanced Central Power Electrical Generation Plants using hybrid technology with hydrogen co-production	High (near zero emissions, very high efficiency, potential H_2 co-production)	(1) NA/NA/2,000 (2) <$1.00/kg, mass production	10 to 20 Years Challenges are cost & coal gasification/ Major technology advancement required	(2) FCV PEM Spec
	PEM FC (DG) – used in: (1) Station load leveling via continuous power utilizing hydrogen from excess over refueling production (2) Backup power (3) Peaking Power	Medium-High (near zero emissions, medium high efficiency, low value waste heat)	(1) 10,000/3,000/ 1,000	Commercially available now at 5kW	
	IC engines on H_2 (DG) MTGs used in: (1) Station load leveling via continuous power utilizing hydrogen from excess over refueling production (2) Backup power (3) Peaking Power	Medium (very low emissions, medium value waste heat, medium efficiency with CCHP)	(1) Current Pricing $800/kW; Expected Pricing: $600/kW Potential <$500/kW	Natural gas, Landfill gas and Digester gas with < 5% Hydrogen commercially available now. Hydrogen under development with UCI APEP Near commercial Barriers include safety standards compliance, and lack of H_2 infrastructure Opportunities include here-and-now transition pathway to H_2; no stranded ICE manufacturing infrastructure; no radical new technology – for users or maintenance;	

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	IC engines (DG) Gas Turbines used in: (1) Station load leveling via continuous power utilizing hydrogen from excess over refueling production (2) Backup power (3) Peaking Power	Medium (low emissions, high value waste heat, medium-high efficiency with CCHP)	1,800/1,200/1,000 potential <$400/kW	Commercially available now	
	IC engines (DG) Reciprocating used in: (1) Station load leveling via continuous power utilizing hydrogen from excess over refueling production (2) Backup power (3) Peaking Power	Medium (low emissions, high value waste heat, medium-high efficiency with CCHP)	1,000/800/400 potential <$200/kW	Commercially available now	
	Fuel Cell/Gas Turbine SOFC "Hybrid" (DG) used in: (1) Station load leveling via power utilizing hydrogen from excess over refueling production (2) Co-Production of Hydrogen	High (near zero emissions, very high efficiency high value waste heat, high potential for H_2 co-production)	NA/3,000/1,000	High cost, low volume, parts count are present challenges SECA & environmental issues are main opportunities (1) Pre-commercial in 2006 (2) Commercially available in 2008, widespread with SECA technology after 2012	(2) FCV PEM Spec

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
Stationary Fuel Cells - Energy Stations[d]	Molten Carbonate Fuel Cell – high temperature (DG) – used for: Baseload Local Client with Efficient Use of Waste Heat Recovery	High (near zero emissions, high efficiency, high value waste heat, potential H_2 co-production)	FCE projects $3/kg for 250 kW unit, serving 25 cars/day, for 1000 kW unit 2.2 $/kg and 100 cars per day competitive	Commercially available now (2) Now- with product refinement and increased manufacturing volume through large order or Federal and/or State development contract	(2) FCV PEM Spec
	Phosphoric Acid FC – Low Temperature (DG) – used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	Medium-High (near zero emissions, medium high efficiency and waste heat value)	4,500/3,000/NA	Commercially available now	
	Solid Oxide FC– High Temperature (DG) – used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	High (near zero emissions, high efficiency, high value waste heat, potential H_2 co-production)	(1) NA/4,000/ 2,000 (2) $3/kg for 250 kW unit, serving 25 cars/day, for 1000 kW unit 2.2 $/kg and 100 cars per day competitive	Demonstrations and pre-commercial now/high cost, low volume, parts count are present barriers/SECA & environmental issues are main opportunities Pre-commercial in 2007 (2) Commercially available in 2010, widespread with SECA technology after 2012	(2) FCV PEM Spec
	Proton Exchange Membrane (PEM) FC (DG) – used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	Medium-High (near zero emissions, medium high efficiency, low value waste heat)	(1) 10,000/3,000/ 1,000	Commercially available now at 5kW	

[d] Energy Stations. Stations designed specifically for the provision of DG power and waste heat recovery AND situated where the real estate can be shared for hydrogen refueling. The strategy is to provide an economically viable enterprise (distributed generation of power and waste heat recovered products) and allow the emerging hydrogen refueling infrastructure to "piggyback" in the early years of evolution. The station can evolve, as desired, to integrate the DG with the hydrogen refueling (e.g., use of a high-temperature fuel cell with hydrogen co-generation) and to add other fueling products (e.g., natural gas, gasoline, diesel, EV charging) as deemed viable by the developer.

For Molten Carbonate FC. Capital costs for H2 recovery are $475K for 250 kW unit and $1,090 for 1MW unit.

Studies conducted by the Collaborative show that energy operating costs can be reduced by more than a factor of 2 through use of co-generating fuel cells (based on typical electric and natural gas utility rates in force today). The associated payback period can be attractive to both private and public investment

Incentive and buy-down programs, common today, can substantially reduce the costs cited.

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	IC engines (DG) MTGs used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	Medium (very low emissions, medium value waste heat, medium efficiency with CCHP)	(1) Current Pricing $800/kW; Expected Pricing: $600/kW Potential <$500/kW	Natural gas, Landfill gas and Digester gas with < 5% Hydrogen available now. Hydrogen under development with UCI APEP Commercially available except for hydrogen capability (under development)	
	IC engines (DG) - Gas Turbines used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	Medium (low emissions, high value waste heat, medium-high efficiency with CCHP)	1,800/1,200/1,000 potential <$400/kW	Commercially available now	
	IC engines (DG) Reciprocating – used in: Baseload Local Client with Efficient Use of Waste Heat Recovery	Medium (low emissions, high value waste heat, medium-high efficiency with CCHP)	1,000/800/400 potential <$200/kW	Commercially available now	
	Fuel Cell/Gas Turbine SOFC "Hybrid" (DG) used for: Baseload Local Client with high fuel to electricity efficiency	High (near zero emissions, very high efficiency high value waste heat, high potential for H_2 co-production)	NA/3,000/1,000	Demonstrations and pre-commercial now/high cost, low volume, parts count are present barriers/SECA & environmental issues are main opportunities Pre-commercial in 2006 (2) Commercially available in 2008, widespread with SECA technology after 2012	(2) FCV PEM Spec
	Ag pumps Electrically driven by fuel cell or engines on H_2	High - lower emissions	High but as other uses increase demand and cost reduced	Now/no OEM or focus of suppliers Based on demand	Depends on use
	Telecommunica-tions repeater stations	Reduced batteries; reduced fuel/labor to service batteries; reduced genset noise, fuel spills, emissions	$3,000/kW $x,xxx/kW $x,xxx/kW	Pre-commercial direct-hydrogen units available for back-up power. Reliability too low & cost too high for applications requiring primary power. Near term for back-up applications. Systems for primary power available 2008-2010. Grid-independent available before 2010.	Compressed gas; >99.95% pure, <1ppm CO
Refueling	Permanent Service	Very good for stations and	Initial cost depends	Permanent stations are available with onsite	Stations can be designed

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
stations	Stations	infrastructures that provide low GHG and criteria emissions, and high well-to-tank efficiency. Metal Hydride for safe bulk storage and compression being developed; underground LH_2 storage tanks and LH_2 dispenser on the station being developed.	on design & capacity, order of $1M now and decreasing in future	production (electrolyzer or reformer) or liquid or compressed hydrogen delivered from central plant. Codes and standards are occasional challenge. A variety of permanent hydrogen station types, each with specific tradeoffs, are available for immediate installation	to dispense hydrogen with any purity specification
	Tube trailer stations	Tube trailer stations can provide refueling with lower initial cost but higher life cycle cost than permanent stations	Initial costs depend on design and site specifics, but generally less than permanent stations	Tube trailer station cost effectiveness best when station is very near to plant. Codes and standards are occasional challenge. Tube trailer station technology is ready to support initial requirements, but long-term benefits are not attractive. Only attractive for low hydrogen demands on the stations. The higher the hydrogen demands on the station the higher the volume of traffic for hydrogen delivery.	Hydrogen specifications depend on requirements, but very high purity hydrogen is available from most plants.
	Home refueling stations	System could potentially provide home electricity and heat in addition to vehicle refueling.	Costs are unknown because concept is developmental.	Concept being developed and tested. CNG home fueling is much more mature but still not commercial. Codes, standards, and permitting issues. Commercial availability TBD.	Presumably, system can be designed to produce hydrogen meeting any specifications.
	Portable refueling stns – mobile refuelers	Mobile fuelers can provide refueling for hydrogen vehicle displays and other temporary needs. Societal benefits are negative, but they may facilitate future societal benefits.	Mobile fueler services are contracted, or fuelers may be leased or purchased. Initial costs are very low and $/kg costs are very high.	Mobile fuelers are available. Code, standard, and permitting issues may exist in some situations. Ready right now. Technology may improve and costs may decrease in future. Only attractive for low hydrogen demands on the stations. No cost-efficient extension possibilities to increase rated output when increasing hydrogen demand.	Mobile fuelers can dispense hydrogen meeting any specification.
Fuels Applications	On-board blending H_2 and LNG	High – could prove to be most cost effective and substantial way to use H_2 in early corridor; Enables existing NG infrastructure and corridor-traveling NGVs to be used for H_2 development.	$XXk for vehicles; $XXXk for stations, dependent on the extent of modification necessary	No existing technology; One company identified who is developing on board blending. However, much interest expressed in the business opportunity by other firms. Demo project in 2005; Commercially available by 2007.	20% blend with natural gas is optimum – produces 50% reduction in NO_x from NG baseline.

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
Portable/ Consumer Applications	Various small, portable devices – e.g. cell phones, computers, electronic devices, power tools, emergency lighting, and portable generators.	Portable fuel cells are typically intended as replacements for batteries or small ICE gensets with the benefits of increased run time and reduced noise, emissions, and maintenance respectively.	Generally very expensive at present compared to incumbent consumer power products. However, specialized applications show economic advantage for FC products under current conditions, with costs expected to decrease significantly in the years ahead.	Portable fuel cell (FC) products have reached the marketplace. Most of these products are targeted toward military or industrial applications, or are intended as demonstrator units to spark OEM interest, but for the most part are too expensive for the general consumer. Hydrogen supply, transportation, and refill infrastructure also present challenges to the consumer. A number of small hydrogen FC products are currently available from companies like; Ballard, Protonex, ReliOn, and Voller Energy. Heliocentris is marketing University level fuel cell (FC) educational systems and Jadoo Power has introduced FC power systems tailored to professional video camera and remote surveillance applications. Numerous other companies are involved in prototype demonstration projects that could commercialize in the next few years.	Fuel cell grade hydrogen is a requirement for most portable FC devices. Storage of sufficient quantities in a lightweight, compact package favors metal hydride technology. Direct methanol FC technology is gaining popularity for small consumer electronic devices. (Prototypes are available, but methanol is forbidden on passenger aircraft.)
	APUs: Airport ground support	Reduced Airport Pollution from Aircraft & GSE. Reduced VRLA Batteries for EVAGE	Cost of GSE dependent on application.	Improvement in fuel cell system Reliability; Cost reduction; power density; fuel cell system hardening Pre-commercial busses, and stationary fuel cell generators are available. Universal power module approach could speed adoption for tugs, carts, lifts, etc.	>99.95% pure, <1ppm CO
	APUs: Truck Stops	Reduced pollution, reduced engine wear, reduced fuel costs, quieter truck cab	IdleAire cost is $1.25/hour for basic service. Cost needs to compete with cost of diesel fuel. Remote (off-grid) sites could become economically viable prior to 2010.	Reliability too low & cost too high to compete with grid power. Codes for siting fuel cell systems. Fuel delivery costs and fuel security at remote truck stops. Technology ready before 2010.	>99.95% pure, <1ppm CO
	Remote sensing equipment	Increased runtime compared to batteries	See portable applications above	See portable applications above Several companies are testing fuel cell power supplies for remote sensing equipment for military, and homeland security applications, and in water/air quality sampling equipment	Fuel cell grade hydrogen is a requirement for most portable FC devices. To store sufficient quantities of hydrogen in a compact

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
					unit, most systems rely on metal hydride technology
	Cell phones	Substantial increase in operating life envisioned depending on fuel source		Most cell phone manufacturers have active programs to develop direct methanol fuel cell power modules. Air travel presents a significant barrier as methanol is currently prohibited on passenger aircraft. Prototypes in testing now. Commercial products planned for 2005-2006.	Hydrogen is not required in direct methanol fuel cell technology
	TV News Cameras, etc	Increased runtime, lighter weight, and faster recharge compared to incumbent batteries	Lifecycle cost of FC system is competitive with battery technology at current levels	Jadoo Power Systems is selling their NAB II system - a fuel cell power module replacement for batteries used on professional video cameras. The NAB II system was introduced to the broadcast news industry in April 2004.	The NAB II system uses a metal hydride storage canister
Storage	Compressed hydrogen storage	Not applicable (benefits depend on production through application and are relatively independent of storage mode)	DOE estimates and goals: 5,000&10,000 psi now = $12&16/kW-hr, 2010 goal = $4/kW-hr 2015 goal = $2/kW-hr	3,600 & 5,000 psi compressed hydrogen tanks are available now and they are the most commonly used hydrogen storage mode. However, large, heavy, and expensive tanks are required for commercially viable vehicle range. Current R&D focusing on 10,000 psi and cost reduction. These should meet DOE 2010 but not 2015 mass & volume goals. Issues include safety certification, full-fill capability, conformal shapes, and cost. Most FCV manufacturers not enamored with, and don't desire to use in volume production vehicles.	Not applicable
	Liquid hydrogen storage	Not applicable (benefits depend on production through application and are relatively independent of storage mode)	DOE estimate and goals: $6/kW-hr now, 2010 goal = $4/kW-hr 2015 goal = $2/kW-hr	Liquid hydrogen has high density so tanks have relatively low mass and volume. Liquid hydrogen tanks, which are similar to LNG tanks, are available now (e.g. hydrogen BMWs). Issues include venting (after a certain time-period of non-use of the application) and cost of infrastructures that include liquefaction (positive issue of the central liquefaction is the high flexibility of this concept: the hydrogen can be delivered to the stations where it is needed and in the quantity where it is needed). Liquid hydrogen fuel tanks with advanced vapor venting avoidance or management, conformal shapes, and liquefaction energy recovery are being developed.	Not applicable

Technology Application Category	Technology End Use	Societal Benefit — Tank to Wheels	Cost: Now; 2010; Beyond	Availability/ Challenges / Opportunities / Rollout Timing / Technology Readiness	Hydrogen Specifications
	Metal hydride storage	Not applicable (benefits depend on production through application and are relatively independent of storage mode)	DOE estimate and goals: $16/kW-hr now, 2010 goal = $4/kW-hr 2015 goal = $2/kW-hr	Hydrogen vehicles with, commercializable Ovonic low-pressure metal hydride storage systems are currently being road tested. Current systems have moderate volumetric energy density (when heat exchanger is included); systems tend to be relatively heavy. Inherently safer than high-pressure compressed storage; more efficient than either liquid or compressed. Separately, DOE is also investing several tens of million $ in advanced complex metal hydride (e.g., alanates) R&D. Goals are high hydrogen release with small temperature increase and low cost. Success timing is uncertain.	Not applicable
	Chemical hydrogen storage	Not applicable (benefits depend on production through application and are relatively independent of storage mode)	DOE estimate and goals: $8/kW-hr now, 2010 goal = $4/kW-hr 2015 goal = $2/kW-hr	This class includes slurries or solutions that release hydrogen through reactions, e.g., with water. There is overlap between this technology category and some metal hydrides. Sodium borohydride catalytically reacted with water has been demonstrated in an experimental Chrysler Natrium. DOE is investing several tens of million $ in advanced chemical hydrogen storage R&D. This technology requires significantly different vehicle and infrastructure system to manage spent fuel.	Not applicable
	Adsorbed hydrogen storage	Not Applicable (benefits depend on production through application and are relatively independent of storage mode)	Technology too nascent to project potential performance or cost. DOE goals: $4/kW-hr by 2010 and $2/kW-hr by 2015	This class includes molecular hydrogen adsorbed in carbon structures at low temperatures and desorbed when temperature is increased. This technology is not yet being tested on vehicles. DOE is investing several tens of million $ in advanced adsorbed hydrogen storage R&D. Emphasis is on carbon nanotubes with high surface area relative to total mass and volume.	Not applicable

3. Commercialization

As part of the Rollout Strategy Topic Team, the Commercialization subgroup adopted a goal to identify steps to accelerate the commercialization of the Governor's Hydrogen Highway. We assumed that a "business-as-usual" approach would not lead to the achievement of the goals of Hydrogen Highway, and that we would not be constrained in brainstorming ideas by any political considerations.

To gather a diversity of views, 18 participants gathered through meetings and conference calls to generate ideas. These participants represented energy companies, automobile manufacturers, fuel cell suppliers, and government. Although we generated more than 20 ideas, we settled on seven high-priority items.

1. Standardize permitting process for hydrogen fueling stations. Phase II activity

Pros	Cons
Will reduce costs of fueling stations.	Lengthy (years) process to develop and adopt standardization.
Several groups in the process of developing and adopting standardization guidelines.	Development of standardization guidelines generally undertaken by voluntary groups. Unclear who or what is lead person/agency.
	Even after the standardization process there is no guarantee that local or state governments will adopt the proposed guidelines, protocols, ordinances, and regulations that emerge from the process.

Means of Implementation	Develop resource materials for local government use such as permitting guidelines or model codes and ordinances. Need to recruit a champion to serve as catalyst, organizer and task master to implement tasks. Need to organize experts to help develop resource materials. Need to develop data base and case studies of previous hydrogen refueling stations. Need to develop training program for local officials.

2. *Capture greater economies of scale for distributed hydrogen production from reformers, wind, photovoltaics, and renewables. Phase I activity.*

Pros	Cons
Lowers production and distribution costs for hydrogen.	Reformers, electrolyzers need for greater reliability.
Takes advantage of existing distribution systems such as natural gas pipelines.	Costs in short term would still be greater than conventional fuels.
May help to move towards renewables.	

Means of Implementation	Need for significant, steady, near-term hydrogen demand source such as stationary applications. Site smaller hydrogen production facilities near end users. Encourage wider use hydrogen/natural gas blended fuels. Encourage use of hydrogen in internal combustion engines.

3. *Capture greater economies of scale for fuel cell stack production. Phase III activity.*

Pros	Cons
Lowers costs of fuel cell stacks	Greater economies dependent upon demand for fuel cell stacks.
	High initial capital costs for tooling and automated production facilities.
	Cost factors per kilowatt-hour still may be high after factory production of fuel cell stacks.

Means of Implementation	Need to show fuel cell technical viability.

6. *Need for government assistance. Phase I activity.*

Pros	Cons
Absolutely vital for hydrogen to be commercialized.	Government procedures and protocols may impose unacceptable conditions for technology development such as the lack of confidentiality.
Can impose regulations and mandates in addition to incentives.	Can be difficult politically, public dollars are difficult to get.

Means of Implementation	Strengthen partnerships. Absorb lessons learned from previous alternative fuel programs. What worked, what didn't. Create funding mechanisms, but avoid taking funds from existing programs such as Moyer. Adopt policies for concerted greenhouse gas controls. Assist in research and development. Develop effective incentive programs for stationary, vehicles, infrastructure, and fuels. Study previous incentive programs to determine effectiveness and ease of administration. Assist in developing sustainable business case for developing technology and investing in hydrogen. Assist in public education program. Encourage government to be first customers of technology and fuel. Ensure incentives are consistent with Federal EPAct and those proposed in the Federal Energy bill. Close loopholes that allow fleet purchasers to avoid complying with measures of such bills. Develop infrastructure incentives to mitigate the capital investment and, in many cases, lost gasoline/diesel pump revenues. Analyze options for incentives such as: state vehicle sales tax exemptions, registration/licensing/livery fee exemptions, state income tax deductions equal to a substantial portion of the incremental vehicle cost, free parking, free fuel, HOV lane access, allowing H_2 fueled taxis to move to the front of the queue, adding incremental taxi medallions for hydrogen fueled vehicles, etc. Develop outreach programs such as ride share programs offering attractive commuting alternatives: e.g., hydrogen shuttle bus or "ride share" bus "offices" with free broadband WiFi access, personal media stations (satellite TV/Radio), morning newspapers, etc. Require new shuttle buses and/or maintenance/support vehicles (e.g., aircraft tugs, fuel tankers, food service vehicles) at selected airports to be hydrogen fueled.

5. *Increase gasoline tax and use proceeds to fund incentives for vehicles. Phase I activity.*

Pros	Cons
Provides for steady source of funds and could be major bucks.	Difficult to impose politically.
Increased cost for conventional technology will decrease the incremental costs of H_2 technology, making it easier to commercialize.	Competing interests may object such as those advocating the use of a gas tax only for highways and roads.

Means of Implementation	Need to develop campaign to sell higher gasoline tax. Need to best determine timing of proposing and campaigning for this higher tax.

6. *Develop a revenue source and use proceeds to fund incentives for vehicles. Phase I activity.*

Pros	Cons
Provides for steady source of funds and could be established such that the public obligation is met.	Difficult to impose politically.
Increased cost for conventional technology will decrease the incremental costs of H_2 technology, making it easier to commercialize.	Competing interests may object and see the CA H2 Net as usurping funds from other programs.

Means of Implementation	Need to develop funding sources and a campaign to adopt programs for these sources. Need to best determine timing of proposing and campaigning for this higher funding source.

7. *Ensure public access to refueling stations. Phase I activity.*

Pros	Cons
Could help overcome “chicken and egg” problem.	Will cause design of refueling stations to be user-friendly and maintain safety standards.

Means of Implementation	Require any refueling station funded with public funds to be publicly accessible.

4. Lessons Learned

Since the early 1980s, California has made several attempts to expand the fleet of alternative fuel vehicles to help improve air quality and reduce petroleum dependence. While several have suggested that these previous efforts were failures, California still has the most numerous and diverse set of vehicles and infrastructure of any state in the nation. Our successes have come from specific fleet applications and building appropriate infrastructure to support these vehicles. To introduce hydrogen as an alternative fuel to petroleum, we will need to ensure that the lessons learned from the previous programs are well understood.

4.1 The Chicken and Egg Syndrome

When California began investigating the use of methanol for transportation applications in the 1980s, the first major problem, "Which comes first, the fueling station or the vehicles," had no real good solution for light duty vehicles. For methanol, the California Energy Commission helped pay for a portion of slightly more than 60 refueling stations to support 13,000 fuel flexible and dedicated vehicles.

The California Energy Commission entered into agreements with seven oil companies in the early 1990s to establish up to 100 stations. At the time several automobile manufacturers offered different models that could operate on both methanol and gasoline. Although the state and manufacturers combined efforts to place as many of these vehicles as possible, sales by the major manufacturer's standards were low. Even worse, despite well attended and covered press events, the dual fuel nature of the vehicle led to very little methanol used. In five years after the introduction of these vehicles, the manufacturers stopped making methanol vehicles, and the oil companies closed the methanol fueling pumps.

Based on this experience, having the means (more than 10,000 methanol vehicles at their peak) and the opportunity (more than 60 methanol fueling stations to support these vehicles) was not enough to make methanol a success. According to Rogers and McNutt (DOE) [26], the vehicles operating on methanol simply did not meet the needs of the general consumer. While we believe that this was a principal cause, those of us involved in the methanol program in California back then know that the problems were more complicated than suggested by Rogers and McNutt. However, if we go to the bottom line, enough factors combined to reduce the commercialization of methanol.

We found that the "chicken and egg" problem probably was a lesser issue than convenience to refuel. Drivers with a choice of using methanol or gasoline had little compelling reasons to go out of their way to refuel with methanol when the corner gasoline station was so handy. The Energy Commission staff found that several drivers of these methanol vehicles did not even know their vehicles could refuel with methanol.

4.2 Niche Applications

California has had programs to encourage the use alternative fuels in transportation since the early 1980s. In these 20 years, the State has accumulated the most diverse and most numerous alternative fuel vehicles and infrastructure of any state in the country. Our best estimate for vehicles currently operating in California is presented in Table 4-1:

Table 4-1. Estimated Numbers of Alternative Fuel Vehicles Currently Operating in California

Alternative Fuel	Number of Vehicles
Ethanol	172,000[a]
Plug in Battery Electric Vehicles	2,300[b]
Natural Gas	30,000[c]
LPG	33,000[d]
TOTAL	237,300

[a] California Energy Commission, Transportation Fuels Office, April 2003 Department of Motor Vehicles data base search results.
[b] TIAX, LLC, California Clean Fuels Market Assessment, 2003 prepared for the California Energy Commission, August 2003, p. 35.
[c] California Energy Commission, Transportation Fuels Office, April 2003 Department of Motor Vehicles data base search results.
[d] California Energy Commission, "ABCs of AFVs," November 1999, p. 63. This number is an estimate based on data from the Department of Energy's Energy Information Agency. Estimating the number of LPG vehicles is difficult since most of these vehicles are conversions and not from original equipment manufacturers. The DMV database would not have the proper codes to recognize these vehicles as LPG.

The total number of alternative fuel vehicles is still dwarfed by the total number of conventional vehicles registered in California (23,000,000). We could not even claim that all of the alternative fuel vehicles listed here use alternative fuels. We believe with near certainty that very few of the ethanol fuel flexible vehicles (FFV) use ethanol since only three E85 refueling stations exist in California today [27].

Although we could conclude that our 20 years of effort has had minimal results, we believe that we met with some success in certain specific market niches. Natural gas vehicles may have shown success in capturing significant market shares in segments of the vehicle populations.

4.2.1 Natural Gas Transit Buses

In 1991, North County Transit District obtained six natural gas buses with the Cummins L10 engines and became the first transit agency in the State to use natural gas transit buses. Since then, 26 other transit agencies acquired natural gas transit buses and by

2003, nearly 4,000 of the 8,500 transit buses in California were natural gas powered [28].

Figure 4-1 shows the yearly gains of market share for natural gas buses within the transit segment.

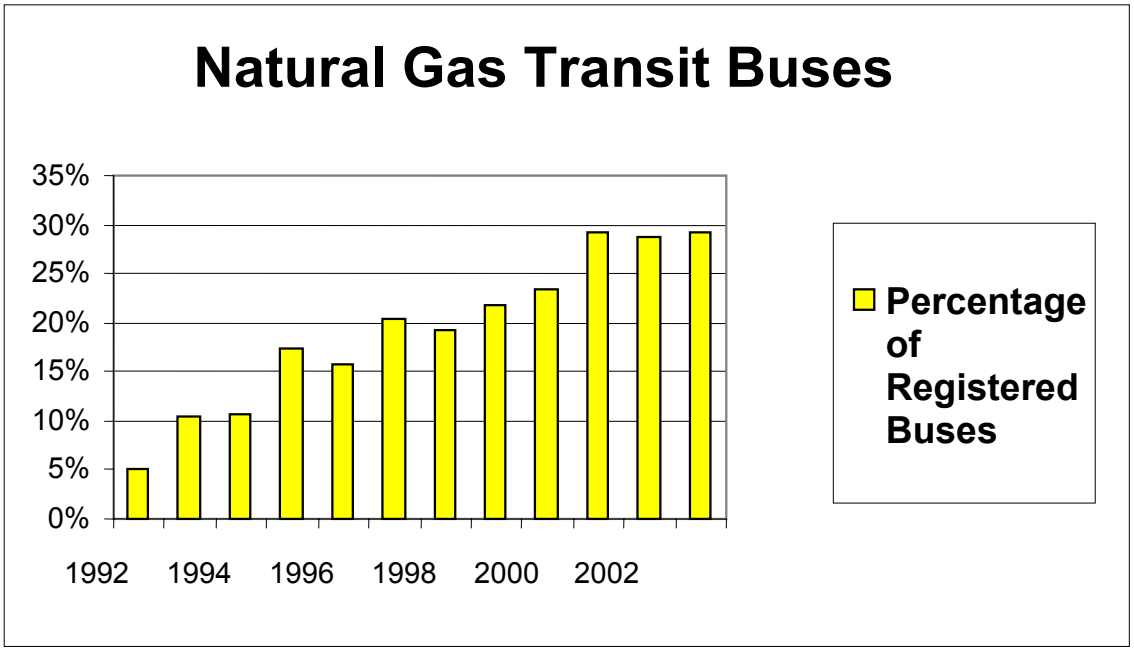


Figure 4-1. Annual Gains in Market Share for Natural Gas Buses within the Transit Segment in California — 1992-2002

For this specific segment of the transportation market, we can say that we have met some success in diversifying from petroleum fuels. Several factors contributed to attaining this market penetration. The biggest is that the Federal Transit Administration provides 80 percent of the capital for natural gas buses [29]. For a $330,000 natural gas bus, the transit agency pays only $66,000. Transit agencies can further reduce these costs with grants from state and local government agencies. These grants ranged from $10,000 to $20,000 per bus depending upon the emission reduction potential compared with standard diesel buses [30].

California transit agencies are also under regulatory requirements that favor the use of alternative fuel buses. The California Air Resources Board adopted their transit bus emission regulations in 2000 that required each transit district in the state to declare a path for compliance – a diesel path or the alternative fuel path. Transit agencies under the diesel path must meet more stringent emission regulations sooner than those agencies under the alternative fuel path. In 2004, transit agencies under the diesel path can buy diesel buses that meet an emission standard of 0.5 grams per brake-horsepower hour [31]. At this time no diesel engine for transit buses meets this standard. As a result, diesel path transit agencies cannot buy any new diesel bus,

prompting one bus manufacturer based in California to say that they've written off the entire California transit bus market.

On the other hand the 26 transit agencies on the alternative fuel path have greater flexibility. Two natural gas transit bus engines are certified for sale in California.

The final factor in enhancing natural gas transit buses is the fleet rule for transit agencies in the South Coast AQMD. Beginning in July 2001, all transit districts in the South Coast Air Basin must purchase alternative fuel transit buses [32]. Already more than 50 percent of all of the natural gas buses in the state operate here. Assuming that the remaining diesel buses in the South Coast Air Basin is switched to natural gas buses, transit agencies could buy another 2000 natural gas buses.

In summary, several factors combined to make the decision to purchase natural gas buses advantageous. Transit agencies had access to funding from several sources that minimized the cost of the bus. At the same time state and local regulations made the diesel path a very expensive route. Going with natural gas turned out to be a relative no brainer.

4.2.2 Refuse Haulers

The California Department of Motor Vehicle database shows that 239 natural gas refuse haulers were registered in 2002 [33]. This is a small fraction of the 12,600 refuse haulers statewide. However, we know that grants from local air districts will provide partial funding for the incremental costs of more than 900 new natural gas refuse haulers.

While we can see parallels with transit buses, we see important differences that will affect the rate of market penetration. Figure 4-2 is a graph of the increase in the number of refuse haulers for the three years that we have data.

Like transit buses, refuse haulers and refuse hauler operations have desirable characteristics to use natural gas. These typically operate on fixed routes, fuel from a central fueling location, and serviced at the local government's service centers. Manufacturers have developed a couple of natural gas engines that can be used in refuse haulers and provide some choice to local governments, although still small compared with the number of diesel engines.

Funding for refuse haulers is nowhere near the amount available for transit buses. Local governments use their capital procurement process and local funds to pay for the trucks and some local air districts provide funding to cover a portion of the incremental costs of the trucks.

Although California does not have specific emission regulations on refuse haulers, these still must comply with increasingly stringent diesel engine emission standards. However, these standards alone do not cause operators to purchase natural gas trucks since, for now, certain diesel engines will meet the current emission standards.

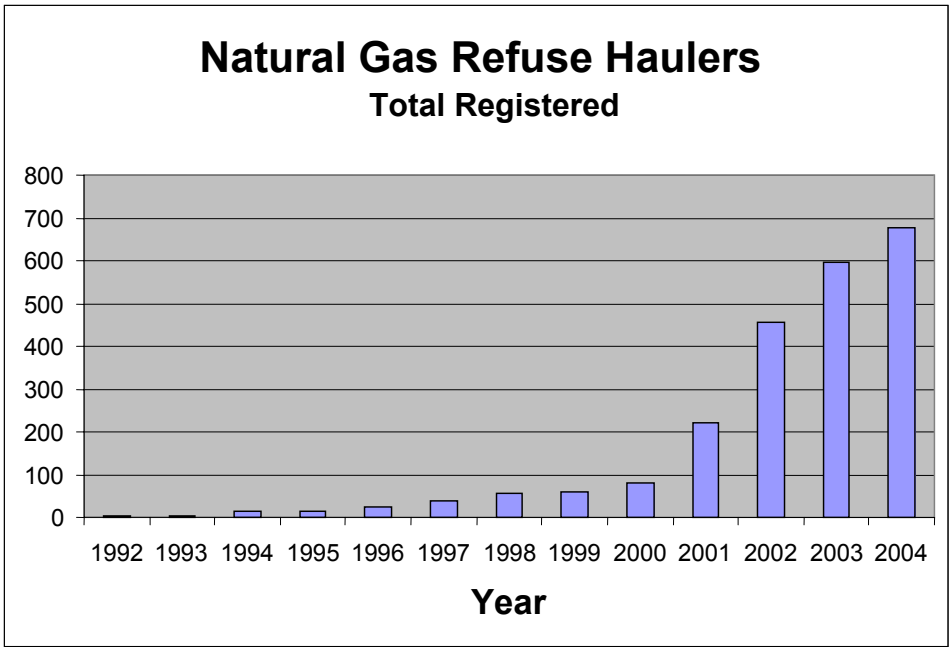


Figure 4-2. Annual Totals of Natural Gas Refuse Haulers Registered in California — 1992-2004

In the South Coast Air Basin, the South Coast AQMD adopted Rule 1193 that requires all refuse hauler operators of 15 vehicles or more must buy alternative fuel refuse haulers whenever replacing or adding to their fleet [34].

Beyond these niche applications, the total number of natural gas vehicles in California is shown in Figure 4-3.

The growth of natural gas vehicles has decelerated and may reverse since Ford and GM decided to drop some or all of their natural gas vehicles from their product line. We should add also that a large majority of the light duty vehicles are dual fuel vehicles, and we suspect that a small fraction of these vehicles use natural gas. The Department of General Services dual fuel natural gas vehicles operated on gasoline exclusively due to the lack of a fueling station at the state garage.

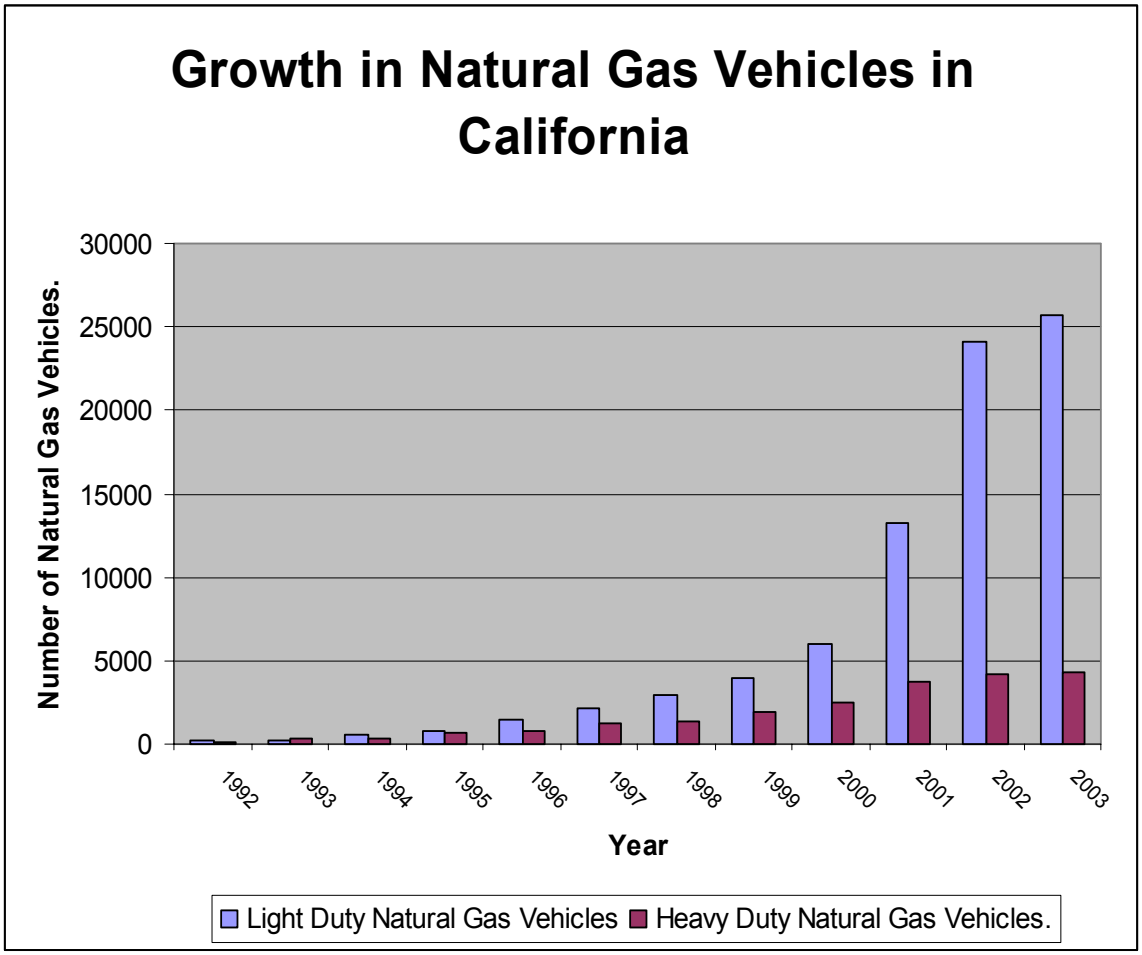


Figure 4-3. Total Numbers of Natural Gas Vehicles in California, by Year — 1992-2003

4.2.3 Future Potential Markets

In reviewing the database from the Department of Motor Vehicles, several types of vehicles in California could be fertile markets for hydrogen fueled cars. Table 4-2 shows the current population of several types of vehicles in the state. With further investigation, some fleets with these vehicles could also be candidates for successfully deploying hydrogen vehicles. Although millions of research and development dollars go toward light duty vehicles, using a portion of these funds for development of heavier duty vehicles may lead to quicker deployment of hydrogen vehicles.

Table 4-2. Current Population of Selected Types of Vehicles in California

Vehicle Types	Number of Vehicles in California
Non Transit Buses	49,000
Vans	88,800
Motorized Homes	237,000
Utility Trucks	25,500
Dump Trucks	38,000

4.3 The Role of Incentives

In an effort to increase the number of alternative fuel vehicles, California has adopted at one time or another incentives to cover the incremental cost of an alternative fuel vehicle, subsidies that cover more than the incremental cost, subsidies for fueling stations, subsidies for the fuel, cash payments to the automobile manufacturers to buy down the cost of the vehicle, cash payments directly to the consumer, tax credits, tax deductions, preferential parking, access to high occupancy lanes, and training opportunities.

California has spent well over $500 million in the last 15 years from state and local sources to help alternative fuels become part of the transportation mix. Some programs worked better than others, but none led as yet to sustainable markets.

As noted in several recent papers, efforts to develop an alternative fuel light duty vehicle market have been less than successful. The authors used the California experience to support their conclusions which include the high costs of entry into this market, the independent decision making of the vehicle manufacturers, fuel suppliers, and end users, the unwillingness to pay more for a vehicle that does less, and the ability of gasoline fuel and vehicles to meet any competitive challenge and leave the alternative fuels in its wake [35].

More discouragingly, these papers imply that incentives have a very limited role in market transformation. Apparently, the incentives need to be considerably larger to overcome the limitations of alternative fuels, the superior performance of gasoline vehicles, and the unknown nature of alternative fuels to the average consumer.

Still, incentives are a useful means of introducing new technologies and products. The incentives may attract the trend setters or early adopters who become advocates and willing to take steps to ensure the probability of success. In previous alternative fuel vehicle programs, we found that the average fleet user had little or no inclination to work with the limitations of the technology, fuel, and support system. The transit agencies in Los Angeles, Sacramento, and SunLine were all early adopters in the early 1990s and have since expanded their fleet of natural gas buses notwithstanding a somewhat temperamental engine.

4.4 Conclusions

Based on California's experience with previous alternative fuel vehicle programs, building fueling stations in anticipation of a future influx of vehicles (the "build it and they will come" idea) is probably a wasted investment or an opportunity cost that reduces more effective programs.

Near-term successes are very important even if it is limited to niche applications. The natural gas vehicle model may be the only real success so far for alternative fuel vehicles capturing markets niche by niche. This success may not transfer to the larger vehicle population.

We need incentives, but we also need to ensure in the early days the highest probability of success. We still don't know if we can use any model to translate success in niche applications to the broader market.

5. Hydrogen Production and Delivery

5.1 Introduction

The Production and Delivery Subgroup was tasked with evaluating the various options that could be used for hydrogen production and delivery in terms of availability/industry readiness, technical and economic barriers, and environmental considerations. Hydrogen can be produced using a variety of feedstocks and conversion technologies. The feedstock options include water, natural gas, coal, petroleum, methanol, ethanol, biomass, and organic waste streams. Ultimately, by using these domestic resources we will be able to produce all the hydrogen we will need for the complete conversion of our transportation infrastructure. The various conversion technologies include electrolysis, reforming (principally of natural gas, but also ethanol and methanol), photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass and coal, high-temperature thermochemical, and catalytic membranes. All of these production technologies are being actively researched by DOE's Office of Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT); and other offices within DOE support work that complements the HFCIT Program activities. In addition, private industry is also dedicating significant resources to these efforts.

It should also be noted that in preparing this report, two long-term methods of hydrogen production were evaluated, nuclear thermochemical water-splitting and coal gasification with CO_2 sequestration. It is accepted that both methods are not feasible in California due to regulatory restrictions, concerns regarding public safety and environmental impacts, as well as the political climate. This subgroup is not making a recommendation that these technologies be considered. These technologies, however, were included in order to provide a complete and comprehensive technology assessment and were thus evaluated and included in this report.

In establishing the California Hydrogen Highway Network (CA H2 Net) we must utilize both distributed (that is, hydrogen that is produced at the point of use) as well as centralized production of hydrogen. Because of technical and economic barriers, most of the technologies for hydrogen production listed above will not become practical for either mode of hydrogen production in large quantities until at least the 2015-2030 timeframe. In the near term, that is, the transitional period between now and 2010 when we will establish a widely available hydrogen fueling infrastructure in California, the distributed production options of reforming and electrolysis will play the dominant role. In addition, production of hydrogen at centralized plants using natural gas reforming and delivery of pressurized or liquefied hydrogen by truck will be utilized. This is a logical extension of the current merchant hydrogen market.

The cost figures in the Production and Delivery report, unless otherwise noted in the text, are based on two primary analysis listed in bibliography under Costing Information. For additional information on costs, refer to the Economy report. Note the time horizons of the Economy report are primarily based on current costs, whereas this report is

generally future estimates. In addition, the Production and Delivery report includes some high level indications of technology environmental benefits. For more information on Societal Benefits, refer to the Societal Benefits Topic Team Report.

5.2 Production Rollout Phases

Three phases of hydrogen production technology rollout are considered: Phase I (now-2010), Phase II (2010-1015), and Phase III (post-2015). These phases are briefly described below. Following this, the various technologies that can be used for hydrogen production and delivery are described in more detail. We focus our discussion on Phase I activities and on the technologies that will have the greatest impact this timeframe. More detailed discussions for these technologies are provided that summarize availability/industry readiness, technical barriers, economic barriers, environmental considerations, and 2010 projected cost for hydrogen. For technologies that will have a post-2015 impact, more qualitative descriptions are provided. In the interest of brevity, this discussion is not intended to be comprehensive. A Bibliography is provided at the end of this section that will direct the interested reader to additional resources. Finally, we end this section with our recommendations for what resources will be needed to evolve the hydrogen production and delivery infrastructure.

5.2.1 Phase I

As discussed above, there are three technologies used for hydrogen production and delivery today: on-site electrolysis, on-site reforming, and centralized reforming with delivery by truck. Mobile refuelers are another potential hydrogen refueling option. Collectively, before the end of 2004 these technologies will be utilized in the establishment of nineteen refueling stations/sites in California that are used in a variety of automobile and bus demonstration projects. In addition, one demonstration project involving the delivery of hydrogen by an existing pipeline is scheduled for completion in Torrance in 2004. Several other projects are scheduled to come on-line in 2005. The location of these sites and the specific methodology employed are discussed by the Sites Subgroup. The total potential hydrogen generation capacity at the current sites is approximately 3,800 kg/day, not including the planned hydrogen pipeline in Torrance (capacity TBD). At the various sites, hydrogen is supplied either as pressurized gas with pressures ranging from 2,000 to 5,000 psi, liquefied hydrogen, or as compressed natural gas (CNG)/H_2 blends. None of the sites are accessible to the general public. The chart that follows summarizes current production options. While it is still in much earlier demonstration phase than electrolysis or reforming, biomass gasification is one other technology that offers some promise for further development in Phase I. If it is further developed within this time period, this technology will only lend itself to centralized production, with truck delivery to refueling stations. It is included in the following chart for completeness. The current state of development and areas for further technology development are discussed more fully in the individual sections for the various technologies. The comments provided in Table 5-1 are couched in terms of “if the hydrogen generated could be used for transportation uses in fuel cell vehicles (FCVs)/hydrogen internal combustion engine vehicles (H2ICEVs).”

Table 5-1. Status of Hydrogen Production and Delivery in 2004

Production/ Delivery Option	Availability	Existing Capacity	California Distribution	Environmental Benefit	Cost (Relative to Gasoline)
Distributed electrolysis using grid electricity	Yes	Very low	Localized (very few demonstrations) concentrated in LA, SF areas and Sacramento	Reduced pollutants, but increased GHG emissions	Very high (unless using off-peak)
Distributed electrolysis using renewables (solar, wind)	Yes	Very low	Localized (only a couple of demonstrations)	Zero emissions	Very high (wind potentially more economical in nearer term)
Distributed reforming of natural gas at refueling site	Yes	Very low	On site in several small demonstrations	Reduced pollutants; hydrogen produced from NG reforming and stored on-board and used in a FCV has potential for 41% reduced GHGs relative to gasoline ICEV.	High
Natural gas reforming at large central facilities with truck and pipeline delivery	Yes	High	Concentrated at refineries (SF Bay, LA Basin) and merchant producers (Sacramento, SF Bay, LA Basin)	See above	High (but less than distributed)
Centralized biomass gasification	Yes	Very low	Early demonstration at a couple of sites	Carbon “neutral”	Very high

Utilizing technologies available today, DOE in collaboration with private industry has planned a number of additional demonstrations in California in Phase I. The refueling centers will be co-located with planned vehicle fleet demonstrations by the automobile manufacturers. The specific details of these demonstrations have yet to be made public. It is planned that these DOE/industry co-funded projects will result in an additional 19 to 22 refueling stations in the State. The current and planned refueling sites will be located in the Los Angeles, San Francisco Bay, and Sacramento regions. As is the case today, for distributed production, in the near term only electrolysis and reforming will be widely available. These technologies will be able to utilize the existing electrical grid and natural gas distribution systems in California, and this will allow the establishment of a hydrogen refueling infrastructure to be accomplished more quickly and efficiently. With accelerated development we envision distributed refueling stations that could produce hydrogen in the 50 to 250 kg/day range. In addition, centralized production (primarily at large reforming facilities, with some contribution from biomass

gasification facilities, and perhaps at nuclear sites using off-peak electricity) and distribution of compressed or liquefied hydrogen by truck, rail, barges, and possibly to a limited extent through pipelines will also be available. In areas without natural gas service, distributed reforming of methanol or ethanol could be employed. These energy carriers could be derived from biomass sources. To say that these technologies will be available means that they exist today; that is, there are commercial suppliers of electrolyzers and reformers, and truck delivery of hydrogen, ethanol, and methanol is a well-established part of the existing merchant business in California. It does not imply that there are not technical, economic, logistical, safety/codes and standards issues, and environmental barriers in developing the transitional hydrogen refueling infrastructure. Importantly, in the early years it is unlikely that any method of providing hydrogen will be able to meet the stated DOE goal of $1.50/kg hydrogen at the pump by 2010 (we note that this cost goal is likely to be raised in the near future). This goal was set early on in order to provide the consumer with hydrogen at a cost comparable to gasoline (1 kg of hydrogen is approximately equivalent in energy content to one gallon of gasoline). For less mature technologies, DOE has set more modest cost goals for 2010 and 2015. Nevertheless, we believe that enough hydrogen can be produced using the three methods outlined above at a cost acceptable to many environmentally-conscious consumers and for fleet operators, especially if fuel cell vehicles can fulfill their promise of having much greater efficiencies than gasoline internal combustion engine vehicles, and if appropriate incentives can be applied. While the production and delivery options (other than biomass) for Phase I still result in greenhouse gas and other pollutant emissions (however, in most cases less than for gasoline ICEVs), it is hoped that they will nonetheless lead to the development of more sustainable hydrogen production methods.

5.2.2 Phases II and III

In the long term, 2010-2050, other production technologies will come on-line as further research removes technical barriers and optimized engineering, lower cost materials and systems, mass production, and reduced operating and maintenance costs removes economic barriers. These advanced hydrogen production technologies include photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass and coal, high temperature thermochemical, and catalytic membranes. Many of these technologies make use of renewable resources that have no greenhouse gas or pollutant emissions or are in principle carbon-neutral. It is our vision that by mid-century hydrogen can become the dominant energy carrier; production methods will be regionally dispersed, both centralized and distributed (although increasingly centralized with hydrogen pipelines). In the years beyond 2010 “carbon-free” or “carbon-neutral” production methods will become more and more utilized. In this regard, we note that some methods that are not carbon-free or carbon-neutral could be viable with CO_2 sequestration.

5.3 Production Options

5.3.1 Electrolysis

Technology Overview

Electrolysis systems use electricity to split water into hydrogen and oxygen. This technology has been used for decades in industrial, military and space applications sometimes for the hydrogen value and sometimes for the oxygen value (i.e., life support). There are two types of conventional electrolyzers: alkaline and proton exchange membrane (PEM). One principle difference between the two is in the type of electrolyte they use.

Alkaline electrolyzers use an aqueous solution of potassium hydroxide (KOH) as the electrolyte which has a very high conductivity. The electrolyzer sometimes resembles a tank and has electrodes connected in parallel. A membrane is placed between the cathode and anode, which separate the hydrogen and oxygen as the gases are produced, but allows the transfer of ions. A related design resembles a filter press and has electrolysis cells connected in series; hydrogen is produced on one side of the cell, oxygen on the other. Again, a membrane separates the electrodes. Alkaline electrolyzers typically operate in a balanced pressure mode such that pressure increases in the hydrogen gas also require increases in the oxygen gas unless mechanical compression is supplied on the gas stream. Typical systems can be pressurized electrochemically to around 125 psi; with system redesign and optimization it may be possible to attain higher pressures, perhaps 700 psi. To attain higher pressures external compression will be required.

PEM electrolyzers use a solid electrolyte similar to that used in PEM fuel cells. In this system the electrolyte is a solid ion conducting membrane as opposed to the aqueous solution in the alkaline electrolyzers. The PEM membrane also serves to separate the hydrogen and oxygen gasses, as oxygen is produced at the anode on one side of the membrane and hydrogen is produced on the opposite side of the membrane. PEM electrolyzers typically operate at differential pressures maintaining an ambient pressure on the oxygen side while capable of achieving pressures over 2,000 psi on the hydrogen side.

Both types of electrolyzers interface very well with renewable technologies since they can easily follow the intermittent loads of a renewable resource. In addition, they can operate efficiently up and down the generation range, have virtually instant turn on capability, operate at low temperature and make very pure hydrogen easily suitable for use in a PEM fuel cell.

A third type of electrolysis system deserves mention: solid oxide steam electrolyzers (SOE). These systems are constructed from durable ceramic materials and metal alloys and operate the 700-1,000^{o}C range. Because they operate at such high temperatures, the voltages required for water splitting are reduced. The lower electricity usage results in a lower cost for hydrogen produced. These types of electrolyzers can have appreciably higher efficiencies than the alkaline or PEM electrolyzers and can produce

hydrogen at pressure. Various efforts have been directed towards the development of SOE in the past, particularly in Germany and in the U.S. However, they are still under laboratory development and it remains unclear whether they will be commercialized in the 2005-2010 timeframe.

Availability

Commercial PEM and alkaline electrolysis systems are generally available today in various output ranges from less then 1 kg per day to over 1,000 kg per day. While the technology behind these systems is solid, much work is left to do to optimize the cost, efficiency, safety and simplicity of these systems before widespread distribution is economically feasible. In addition, since the various technologies generate hydrogen at different pressures, there is corresponding development required for compression, storage and dispensing of the gas for fueling at 5,000 to 10,000 psi. Again, the technology to provide this downstream gas handling exists today and is in use in various demonstration projects. However, it also needs to be optimized for widespread commercial use. Expectations are that by 2010 that if the demand is there suppliers will be able to “mass” produce electrolyzer systems in sizes up to 250 kg/day. While there are several improvements in materials and designs that are need to increase system efficiency and durability, the major barrier is in cost.

Costs

Several efforts are underway by electrolysis manufacturers to lower the cost of the systems and improve the efficiency. The DOE has a 2015 goal of $2.85 per kg for hydrogen by electrolysis. The reality is that adequate development work is already in process or in the planning stages to meet the technical requirements behind these costs (e.g. system efficiency improvements, reduction in compression stages). However, the likely scenario is to have a system design in place such that a production volume of say 1000 stations per year would yield those types of costs. Since industry expects that the Hydrogen Highway plus other programs anticipated for that timeframe will fall well short of that type of volume, some increase in costs from those goals should be expected.

The cost of the electrolyzer is governed by only a few simple factors. The first is electricity consumption which relates to efficiency. Another is capital equipment cost. Today, the end-to-end system efficiencies (includes compression, storage and dispensing) according to DOE published reports is around 60 percent. In California the average cost of commercial electricity is $0.1115 per kWh. For a 1,050 kg/day “nth” plant assumption (meaning mass produced, which they are not), assuming installed capital costs of $798/kW and system energy requirement of 53.5 kWh/kg, the cost of hydrogen production is $7.63/kg [36]. Projections are that this cost can be reduced significantly by 2010-2015 with reduction in capital equipment cost, operating and maintenance costs, improved system efficiency, and lower cost electricity (e.g., use of off-peak power). For instance, if electricity were available at $0.035 per kWh the cost of hydrogen would be more like $3.50/kg (we note that in some areas in California, as well as in many parts of the country that electricity costs can achieve this cost range using off-peak power) [37]. A long-term DOE goal is to reduce the installed capital costs to $300/kW.

A third factor is capital cost recovery, which is a factor of cost and utilization. There are many numbers being tossed about regarding the cost to install this type of system to get it ready to fuel vehicles. Without greatly accelerated vehicle deployment, in almost any scenario put forth on the number of cars expected versus the number of stations in the baseline plan, the utilization factor associated with these stations will be pretty low. This will considerably drive up the capital amortization over the output of hydrogen and substantially increase the cost per kg. This will be equally true with any form of capital asset employed in the next 10 years.

The challenge for electrolysis is to decrease the capital cost by more than 50 percent, increase system efficiency, and decrease operating and maintenance costs. Electricity at high cost is a major economic roadblock. However, if renewable resources can be utilized with electricity costs of less than $0.04 per kWh, then the cost of production of hydrogen can easily be brought down. If electricity from nuclear can be utilized, an economically-competitive pathway for hydrogen production is also attainable. No matter what the cost of electricity is, electrolysis will play a large part in the transition to a hydrogen economy in California simply because it is a proven, available technology that is scalable to sizes needed for distributed hydrogen production. It is versatile and easily adaptable to current and future sources of electricity and has a plentiful, entirely domestically-available feedstock (water). Perhaps no other technology can make as broad-sweeping claims.

Environmental Considerations

The simple fact when considering electrolysis for fueling is that you need electricity to make the hydrogen. If that electricity is generated by renewable technologies, there are zero emissions. If the electricity is generated from nuclear power, although zero emissions, there are public safety, environmental consequences, and political issues which make it unlikely in California. Conversely, if that electricity is generated by coal fired power plants, there are increased criteria pollutant and greenhouse gas emissions. California's electricity supply is unique in North America in that a higher percentage of it is "carbon free" (40 to 45 percent compared to 25 percent nationally) so this helps the overall energy/pollution question. California also has specific standards that will insure that any new electricity generation for use in the state would come from very clean and/or renewable resources. In any case, using electrolyzers to begin to develop the hydrogen infrastructure and continue the development of the technology is key both to the survival of the small companies making this equipment and also to achieve the breakthroughs required to allow the efficient marriage of this technology with renewable assets when and as they become more widespread and cost effective.

Table 5-2. Electrolysis

Electrolysis Mode	Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
(a) Distributed using grid electricity	Alkaline and PEM electrolyzers are commercialized. Systems have been built having hydrogen production capacities ranging from less than 1 kg/day to 2500 kg/day (upper end alkaline). Major North American companies include Proton, Stuart, Teledyne, and Hydrogenics. Industry could gear up to mass produce units in 25-250 kg/day capacity in 2005-2010 time frame (ultimately 1,000-1,500 kg/day stations are desired but may not be economical for some time).	System efficiency (currently 60-65%) needs improvement. Eliminate need for costly external compression-develop electrochemical compression or higher pressure cell stacks. Low cost, higher performance, and more durable materials needed, especially for high pressure operation. Improved, simplified cell stack and balance-of-plant designs needed, especially power electronics. Improved manufacturing capability needed (cost reduction, DFMA).	High cost of electricity and high capital equipment cost results in hydrogen cost of $8-$10/kg currently. Capital equipment cost (particularly cell stack) must decrease at least 50%. Operating and maintenance costs must decrease. Low cost electricity must be utilized (e.g., off peak,).	Grid electricity mix can increase greenhouse gas emissions in large scale electrolysis. California has advantage in a relatively "clean" grid (one third renewable; 40-45% "carbon-free" with nuclear included which compares to 25% U.S.-wide). New generation mix will even be cleaner than the current average grid mix. Decreased particulate and NO_x emissions are realized.	$2.85/kg is DOE goal for 2015. Cost of hydrogen in 2010 likely in $3-$4/kg range.
(b) Distributed using renewable electricity	See above	More efficient integration of electrolyzer with renewable electricity sources is needed. Intermittent power creates inefficiency and hydrogen availability problems. Overall system efficiency needs significant improvement.	High capital cost for solar systems in addition to high capital cost of electrolyzer yields hydrogen at much greater cost than $8-$10/kg. Cost depends on if the renewable asset is being used as a primary source of power or if it is mainly feeding other loads.	Zero environmental emissions and allows use of excess renewable power in times where load is below capacity and excess is not being dumped to the grid.	Wind will likely be the only economically viable option by 2010 with wind electricity hopefully costing less than $0.05/kWh. With production tax credits allowing wind to reach $0.025-$0.035/kWh, the cost of hydrogen production could be less than $3/kg.

5.3.2 Reforming

Technology Overview

Reformers generate hydrogen from hydrocarbon or alcohol fuels. The most common technologies are steam methane reforming (SMR), auto-thermal reforming (ATR) and partial oxidation (POX). SMR on a very large scale has been the most common production technology at refineries and central production plants for decades. The hydrogen from these facilities is often piped short distances in vast quantities or truck delivered in either compressed or liquid form. (See Delivered Hydrogen Section.)

The challenge for the developers of on-site reformer developers has been to adapt this tested large-scale SMR technology to a much smaller scale. On-site reforming takes advantage of the existing infrastructures for fuel delivery, such as natural gas or methanol, alleviating the need for truck delivery of hydrogen. Reformers consist of two systems, the hydrogen generating process (SMR, ATR or POX) and the purification and clean-up technology, generally pressure swing adsorption (PSA) or membranes. The high-purity hydrogen generated by the reformer will then be compressed and stored at 5,000 to 10,000 psi for dispensing to the vehicles. At locations which are distant from large-scale, centralized hydrogen production facilities, on-site reformers may provide the lowest cost production of hydrogen.

While the most common feedstock for reformers is natural gas, reformer companies are also working to develop and commercialize technology for other fuels as well. These include other hydrocarbons such as LPG, diesel and gasoline, methanol and ethanol. Efforts are underway to develop ethanol reformers, so that renewables (i.e., ethanol and methanol from biomass) can be part of the emerging reforming portfolio. While the hydrocarbons have an existing infrastructure advantage, ethanol is becoming an increasingly common additive to gasoline. This growing ethanol delivery infrastructure can be leveraged for the renewable production of hydrogen through reforming. Methanol has the added advantage of both an existing liquid delivery infrastructure and the potential for renewable production. Since methanol is both a common chemical feedstock and a common consumer product (windshield washer fluid) and a common racing fuel, the existing liquid delivery infrastructure is in place throughout California. The ability to deliver liquid methanol or ethanol to areas where natural gas is not available makes them candidates for distributed reforming in areas without natural gas service at prices competitive with natural gas reforming.

These on-site hydrogen generators range in size from about 1 kg, or gallon gasoline equivalent, per hour up to 20 kg/hour. Several equipment suppliers have standardized around 5 and 10 kg/hour sizes, which would serve populations of 200 to 500 light-duty fuel cell vehicles, or 100 to 250 internal combustion engine (ICE) vehicles.

Availability

Reformer technology is approaching commercialization with at least a dozen on-site reformers in demonstration throughout the world. Major North American providers of reforming technology for refueling station applications are HyRadix, H2Gen and Ztek.

Table 5-3. Reforming

Production Mode		Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
On-site Reforming	(a) fossil fuels	Reformers are approaching commercialization. Systems have been built having hydrogen production capacities ranging from less than 25 kg/day to 400 kg/day. Active North American companies include ChevronTexaco, H2Gen, Harvest Energy Technology, HyRadix, Plug Power and Ztek.	Cost reduction and reliability are the primary challenges. System efficiency improvement will marginally reduce hydrogen costs. Low cost, higher performance, and more durable components needed. Improved manufacturing capability needed (cost reduction, DFMA[a]).	Capital equipment cost results in hydrogen production cost of $3.50 - $6/kg currently. Capital equipment cost must decrease for the H_2 price to decrease. Operating and maintenance costs must decrease. Final hydrogen price is sensitive to feedstock price; for example natural gas feedstock at $7.30/MBTU (California average industrial price) contributes $1.25/kg to the price of hydrogen.	The most common fuel for reformers is natural gas, or other hydrocarbons such as LPG[b]. Reforming does result in CO_2 emissions, but H2 made from natural gas will reduce CO_2 emissions from FCVs by 45% to 50% compared to gasoline used in conventional cars. Particulate and NO_x emissions from most reformers are negligible.	$1.50/kg is DOE goal for 2015. Cost of hydrogen in 2010 likely in $2.25 – $3.00/kg range depending on reformer size, feedstock costs, station utilization and the return on investment required by the station owner.
	(b) renewable liquid fuels[c] (ethanol from corn or cellulosic biomass, or methanol from biomass)	Reformers are also under development to reform renewable ethanol and methanol at the fueling station. Methanol on-site reformers have been demonstrated in Japan.	Same as above, with the exception of methanol, which is easier to reform than any other fuel[d]	Same as above, with exception of a methanol reformer which will have lower capital cost. Ethanol selling at $1.50/gallon would contribute $3.50/kg to the cost of hydrogen. Methanol is expected to be available at much lower prices. Methanol at $1.50 per gallon would contribute $3.45 / kg to the cost of hydrogen, but methanol at current prices of $0.65 / gal. Would only contribute $1.50 / kg of hydrogen.	Hydrogen made at the fueling station from ethanol or renewable methanol offers the lowest cost near term option to dramatically reduce greenhouse gas emissions. GHG reductions of 60% for corn ethanol to 85% for cellulosic ethanol are feasible.	Cost of renewable hydrogen in 2010 likely in the $4.50/kg range from either renewable ethanol or methanol.

[a] DMFA refers to Design for Manufacture and Assembly; DFMA is a registered trademark of Boothroyd and Dewhurst.
[b] LPG refers to liquid petroleum gas which is primarily propane in North America, but is predominantly butane in other countries.
[c] This option excludes direct biomass gasification to produce hydrogen at a central facility, since that biomass-generated hydrogen would have to be transported to the fueling station, incurring added transportation costs.
[d] Methanol can be reformed at 260°C, whereas all other fuels require temperatures above 600 to 800°C which adds to reformer cost and durability issues.

Production Mode		Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
Central Plant Production	(a) fossil fuels – liquid delivery	Hydrogen is produced in large central plants today, primarily by reforming natural gas. This technology has been commercial for many decades.	None	The cost of liquefaction of hydrogen (20°K or -253°C) nearly doubles the cost of production. The fueling station requires a heavily insulated cryogenic dewar to store the liquid hydrogen, a cryogenic liquid pump, vaporizer, gaseous storage tanks and dispenser. Boil off losses during transfer and storage will add cost.	The electricity used to liquefy hydrogen is equivalent to 30% to 35% of the lower heating value of the hydrogen. The GHG advantage of hydrogen-powered FCVs is nearly cancelled out by the GHGs due to this extra electricity requirement.	The all-in costs of delivered LH_2 including on-site storage, vaporization and dispensing will depend on distance to the LH_2 plant, size of the fueling station, capital recovery factors, etc. For a mature station costs are expected to be in the $2.20 to $3.80/kg range.
	(b) fossil fuels – gaseous delivery	Same as above	No serious technical barriers.	The cost of liquefaction is avoided, but delivering hydrogen in compressed gaseous form is much more expensive than delivering liquid hydrogen. The fueling station also requires a hydrogen compressor, hydrogen storage tanks, and a dispenser	GHGs are cut 45% to 50% compared to burning gasoline in a conventional car. There are no criteria pollutants emitted in the local urban airshed.	The all-in costs of delivered gaseous hydrogen including on-site storage, compression and dispensing will depend strongly on distance to the H_2 plant, size of the fueling station, capital recovery factors, etc. For a mature station costs are expected to be in the $3.20/kg to $5.50/kg range.
	(c) biomass – gaseous delivery	Biomass (energy crops and agricultural waste) gasification combined with PSA or membrane gas cleanup systems can produce fuel cell grade hydrogen. Gasification technology is in the development phase.	Technical barriers include equipment degradation due to various constituents in the raw biomass including potassium, sulfur, etc., variability in feedstock composition and durability of gasifiers in general.	The cost, cost variability and seasonal availability of the biomass feedstock may limit the economics. The cost will also be limited by the same transportation and on-site storage and dispensing costs that affect trucked in hydrogen from central SMRs.	Biomass hydrogen is an excellent pathway to reduce GHGs and dependence on imported oil. Well-to-wheels GHGs are not zero, however, due to the fossil fuel consumed in fertilizer, pesticides, herbicides, farm machinery, and transportation of the biomass to the gasifier and delivery of the hydrogen from the gasifier to the fueling station.	The NRC estimates biomass hydrogen at $7/kg, with future advances in farming efficiency and gasification technology potentially reducing the cost to $3.60/kg.

Reformer-based refueling stations can be found at SunLine Transit in Thousand Palms, CA, at Pacific Gas & Electric in Auburn, CA and at the City of Las Vegas, NV. Ongoing challenges include cost reduction and improved reliability.

5.3.3 Photobiological and Photoelectrochemical

Photobiological Hydrogen Production

Technology Overview

It is a remarkable fact that the same elemental forms of life (e.g., blue-green algae) that first supplied earth's atmosphere with oxygen are also capable of generating hydrogen under special circumstances that must harken back to their initial primitive environment. We owe our existence to such primitive micro-organisms and in the future we may owe our continued high standard of living to them as well, at least in part. Blue-green algae, green algae, purple algae, and photosynthetic bacteria are all being studied for their capability to use sunlight to produce hydrogen. The leading contender to become a commercially viable hydrogen producer is the green algae species *Chlamydomonas reinhardtii*.

C. reinhardtii were first cultured at Berkeley in 1998, where it was found that they would produce hydrogen when switched to a sulfur-deficient anaerobic environment. [38] The hydrogen was produced for only a limited period of time, however, after which the green algae had to be placed back in their normal sulfurous, oxygenated environment in order to revitalize and be ready to continue hydrogen production. Subsequently, researchers at Berkeley managed to produce hydrogen continuously using a series of two flow bioreactors that provide the green algae with environments for hydrogen production and revitalization.

In contrast to electrolysis, which requires electricity to split water, these primitive algae and bacteria are able to produce hydrogen from water using catalytic enzymes that they manufacture. Furthermore, hydrogen production using micro-organisms is scalable, which allows production to be either distributed or centralized. Production can be distributed or centralized because what is mainly needed to produce hydrogen is a proper habitat for the algae and that may vary in size: the press has dubbed this environment "slime ponds." In actuality, it consists of a photo-bioreactor, a means of hydrogen extraction and storage, and, preferably, sunlight. Artificial light could be used, but that would involve using electricity. Since Southern California has an abundance of sunlight, it is a particularly advantageous place for distributive production while Northern California has the advantage of being the center of major research into photobiology.

In its present early stage of development, the limitation to photobiological hydrogen production is inefficiency. The present (solar to hydrogen conversion) efficiency is only 0.5 percent. Besides this limitation, there is the constraint that comes with requiring light. Because they depend upon light, photobiological processes lose efficiency on cloudy days and at greater pond depths and of course are not operational at night. DOE's funding of research into photobiological hydrogen production is aimed at overcoming the limitation on efficiency, and a goal of 5 percent efficiency by 2010 has

been set [39]. The thrust of the current DOE-funded work is on *C. reinhardtii*. The DOE has identified two basic areas in which breakthroughs must be made in order to increase efficiency and reduce costs: genetic engineering and photobioreactor engineering.

Successful genetic modifications would significantly increase the green algae's capability to produce hydrogen by removing inhibitions to hydrogen production within the microorganism itself. For instance, green algae co-produce oxygen, which inhibits the hydrogen-producing enzyme. The size of the chlorophyll antenna that the algae use for direct photobiological hydrogen generation, presents another problem. Under bright sunlight, this chlorophyll antenna absorbs much more light than can be used for photosynthetic electron transport, resulting in heat dissipation and the loss of up to 80 percent of the absorbed light. By inefficiently absorbing so much light, the algae higher up in the bioreactor steal photons from algae at lower levels, reducing overall production.

System engineering systems breakthroughs would significantly reduce cost. Because of the large size of the hydrogen production 'ponds," the photobioreactor cost must be minimized. However, until more information is provided on what materials are appropriate for use in the photobioreactors, it is hard to estimate how low the reactor cost can be made.

Availability

Photobiological hydrogen production today is still at the basic R&D stage. Nonetheless, photobiology has attracted some commercial interest. One company, Melis Energy located in Santa Barbara California, is setting up to create commercial hydrogen using the green algae. Barring an unforeseen breakthrough, however, photobiology is not likely to be commercially viable until after 2015. In order to meet the hurdles of commercial viability several goals have been establish for photobiological hydrogen, including: a) system costs will be able to reach $30/kg by 2010 and $5/kg by 2015; and that b) the biological system will reach 20 percent efficiency for absorbed light (but even with this the system will likely not exceed 5 percent efficiency of light to H_2 conversion by 2010 [40]). To make commercial use of the green algae possible by 2015 and achieve the goal of 5 percent efficiency, researchers are looking to reduce the chlorophyll antenna size of green algae by 58 percent, breed more oxygen tolerant algae, and achieve 6 months continuous hydrogen production by 2010.

Costs

High reactor costs and low hydrogen output are the major roadblocks to commercialization. If the photo-bioreactor's cost can be significantly reduced (to $1/m^2), then photobiological systems with an efficiency of 5 percent can produce hydrogen at DOE's ultimate goal of $2.60/kg [41]. To meet this cost goal, the ideal photo-bioreactor system would use a hydrogen pipeline as a delivery system and would have to be a continuous hydrogen production system with no pressure swing adsorption (PSA) unit; and no compression [42]. More information needs to be collected on photobioreactor costs as well as other costs drivers such as hydrogen collection systems, continuous

bioreactor operation, land area requirements, and capital costs. Understanding these costs is particular important since such investment costs are expected to be almost 90 percent of the expenses involved in photobiological hydrogen production.

The DOE's cost, efficiency, and production research goals for photobiological hydrogen production are given in Table 5-4 [43].

Table 5-4. DOE's Goals for Photobiological Hydrogen Production

Characteristics	Units	2003 Status	2005 Target	2010 Target
Solar-to-Hydrogen Efficiency	%	0.1	0.5	5
Continuous photo-production (Durability)	hours	240	500	1500
Cost	$/kg	N/A	$100	$30

The costs are for low-pressure hydrogen, at the plant-gate. Little is provided in these DOE goals related to actual hydrogen output.

In summation, two breakthroughs are likely to move photo-biological hydrogen production more rapidly to commercialization: (1) An acceptably high rate of hydrogen output, which depends upon solar-to-hydrogen conversion efficiency; and (2) lower photobioreactor costs.

Photoelectrochemical Hydrogen Production

Technology Overview

Photoelectrochemical (PEC) hydrogen production is sometimes described as artificial photosynthesis because it resembles the initial stages of photosynthesis in green plants. What PEC and photobiological systems have in common is the ability to perform photoconversion, which is the act of splitting water into hydrogen and oxygen using light. In its simplest form, a PEC cell accomplishes this conversion using a photovoltaic (PV) semiconductor electrode, a metal counter electrode, and an aqueous electrolyte. When light is incident on the PV semiconductor electrode, the electrode absorbs photons resulting in promotion of electrons to the conduction band and oxidation or reduction of species (in this case, water) in the solution adjacent to the electrode. Electricity flows between the semiconductor and counter electrode. The result is the production of hydrogen and oxygen gases separately at the two electrodes. While inorganic PV systems are favored in research, the investigation of hybrid photovoltaic devices (e.g., metalloporphyrin coated semiconductor electrodes) constitutes a second key research area.

The advantages of PEC systems are similar to the advantages of photobiological systems. They require no external source of electricity, and have no emissions. Hydrogen production using photoelectrochemical systems is scalable. The

photoelectrochemical cells or banks of cells that compose a system can vary in size, and their size variability makes them candidates for either distributed or centralized production. While the efficiency of PEC cells is higher when using the more expensive crystalline materials, solar efficiencies of up to 7 percent can be achieved using less costly amorphous materials (higher efficiencies have been claimed in the literature although these are not generally widely accessible). This level of efficiency is significantly higher than photobiological systems are currently able to achieve.

Electrolyte leakage has been an intrinsic problem with PECs. Recent developments of solid electrolytes have ameliorated this problem. This is a significant breakthrough. However daunting challenges remain.

What has limited both the efficiency and durability of PECs is that these attributes seem to be mutually antagonistic in the materials investigated so far; that is, materials which have been shown to have greater efficiency have tended to be less durable and vice versa. Similarly, semiconductor materials that have the more optimal band gaps for electricity production for water splitting have had disappointingly low visible light spectrum absorption capability and vice versa. PEC systems are also constrained by diurnal operation limitations. Like photobiological systems, they depend upon light and, of course, are not operational at night without the presence of artificial light. For photoelectrochemical systems to be commercially viable, therefore, other breakthroughs will be required (a) to improve the solar-to-hydrogen conversion efficiency of photoelectrochemical systems, (b) to improve semiconductor durability, and (c) to improve PEC design and manufacture for mass manufacturing.

These breakthroughs are expected by the DOE to come principally through the discovery of new materials that are both less costly and more efficient and through low-cost PEC engineering. For instance, because they require neither high-temperature processing nor a exceptionally clean, high vacuum manufacturing environment, organic photovoltaic devices could potentially be used to reduce manufacturing costs significantly below those of inorganic PV-based PEC systems.

Availability

Like photobiological production, PEC technology is still in the R&D stage. It is not anticipated that solar hydrogen production using PEC technology will make a significant impact on hydrogen production until well after 2010. Low volume distributed production is the most logical pathway in the 2010-2025 timeframe.

Costs

While commercial production is years off, in 2004 the DOE set some impressive goals for photoelectrochemical hydrogen production, as shown in Table 5-5 [44].

Table 5-5. DOE's Goals for Photoelectrochemical Hydrogen Production

Characteristics	Units	2003 Status	2005 Target	2010 Target	2015 Target
Solar-to-Hydrogen Efficiency	%	7	7.5	9	14
Durability	hours	100	1,000	10,000	20,000
Cost	$/kg H_2	N/A	360	22	5

These costs are for low-pressure hydrogen, at the plant-gate. No delivery cost or production level goals are currently set for centralized production.

In summation, it is assumed that two breakthroughs would move PEC hydrogen production rapidly to commercialization: (1) the discovery of new materials with 2015 target efficiencies and durabilities, and (2) engineering costs around $5/kg using present dollars.

Table 5-6. Photolytic Hydrogen Production

Production Mode	Development Status / Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost
Photobiological	Photobiological hydrogen production today is still at the basic R&D stage. Barring an unforeseen breakthrough, it is not likely to be commercially viable until after 2015. Two breakthroughs could move photobiological hydrogen production more rapidly to commercialization: (1) An acceptably high rate of hydrogen output, which depends upon solar-to-H_2 conversion efficiency; and 2) lower photobioreactor costs.	In its early stage of development, the limitation to photobiological hydrogen production is inefficiency. Current solar-to-hydrogen conversion efficiency is only 0.5%. These systems are also constrained by "pond" depth and by diurnal operation limitations. Because they depend upon light, photolytic processes lose efficiency to varying degrees on cloudy days and at greater pond depths and of course are not operational at night without the presence of artificial light.	The high cost of photo-bio reactors is believed to be the major roadblock to commercialization.	Carbon neutral process.	$30/kg by 2010
Photo-electrochemical	Like photobiological hydrogen production, PEC technology is still in the R&D stage. Two breakthroughs would move PEC hydrogen production rapidly to commercialization: (1) the discovery of new materials with a 2015 target efficiency of 14% and 20,000 hours demonstrated durability; and (2) more optimal engineering systems to lower cost of hydrogen produced.	PECs currently have low efficiency and durability. These appear to be mutually antagonistic in many of the materials investigated so far; that is, materials having greater efficiency have tended to be less durable and vice versa. Similarly, semiconductor materials that have more optimal band gaps to produce sufficient electricity for splitting water have had disappointingly low visible light spectrum absorption capability and vice versa. Like photo-biological processes, PEC needs light to function.	Though PEC systems don't require high cost crystalline semiconductor materials to operate, the costs of material and manufacturing remain economic barriers	This technology is expected to be carbon-free, but that may depend upon the electrolyte that is used.	$22/kg by 2010; $5/kg by 2015

5.3.4 Coal Gasification with CO_2 Capture and Sequestration

Technology Overview

Hydrogen can be produced at large scale by gasification of low-cost solid hydrocarbon feedstocks such as coal, petroleum coke, wastes or biomass. The feedstock is reacted with oxygen (either pure oxygen or air) and steam at high temperature producing a synthetic gas or "syngas," comprised of hydrogen, carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O), and methane (CH_4). The syngas is further processed in a water gas shift stage to increase the hydrogen content, and pure hydrogen is separated out of the mixture. Coal-to-hydrogen routes are being evaluated because coal is a low-cost, large resource in the United States, and in other countries with high-energy use such as China and India. However, it is recognized that within California itself that coal currently contributes less than one percent to total power capacity, a number that is unlikely to increase in the future. However, it is noted that parts of California import significant electricity generated at out-of-state coal power plants.

A major environmental issue for coal-derived liquid fuels is carbon emissions to the atmosphere during their production and use. However, when hydrogen is made from hydrocarbons, carbon dioxide can be separated, compressed, transported by pipeline and "sequestered" in secure underground storage sites such as deep saline aquifers or depleted oil and gas fields. This would allow continued use of fossil-derived fuels, with near-zero emissions of carbon to the atmosphere. The technologies for capturing, transporting and injecting carbon dioxide into geological formations are well known in the oil industry where carbon dioxide is piped and injected into oil reservoirs for enhanced oil recovery. Several demonstrations of CO_2 sequestration are ongoing in the United States and Europe (U.S. DOE Carbon Sequestration Technology Roadmap and Program Plan 2004). And although carbon capture and sequestration hold promise for fossil hydrogen as a long term, low carbon emitting option, there are many questions that need to be addressed regarding the efficiency, viability, costs, and environmental impacts of long-term CO_2 storage.

Near-Term Technologies, 2004-2010

The chemical process technologies to produce hydrogen at large scale from coal are well established and commercially available. In the U.S., coal-derived industrial hydrogen is a minor player, about 95 percent of hydrogen is made from natural gas, but worldwide about 30 percent of industrial hydrogen is produced from coal-derived syngas (U.S. DOE Hydrogen Program website 2004). Much of this capacity is in coal-rich nations such as China. Despite this large capacity, none of the industrial coal-to-hydrogen facilities currently capture CO_2 (U.S. DOE Hydrogen from Coal RD&D Draft Plan 2004).

Technologies Available in the 2015-2030 Timeframe

Advanced systems for co-production of electricity and hydrogen from coal with CO_2 capture are under development. In 2003, the U.S. DOE announced the $1 billion "FutureGen" program, with the goal of producing electricity and hydrogen from coal,

while capturing and sequestering CO_2. The U.S. DOE Future Gen Program has set a 2015 goal of demonstrating a 60 percent efficient, zero-emission coal plant producing 275 MW of hydrogen and electric power with carbon capture and sequestration at a 25 percent cost reduction over current coal-to-hydrogen technology. (Source: Hydrogen Posture Plan 2004; U.S. DOE FutureGen Report 2004). In addition to funding for the FutureGen Initiative, funding for ancillary coal-to-hydrogen RD&D was $4.9M (FY'04) and $16 M is requested for FY'05.

Scalability

Coal gasification with CO_2 sequestration is inherently a large-scale centralized production option, and hydrogen distribution would be required to refueling stations. This is unlike the case for natural gas steam reforming where onsite production would be possible. Gasifiers, a major contributor to the plant capital cost and the levelized hydrogen cost, exhibit strong scale economies, so large plants are favored. Similarly, CO_2 disposal pipelines and injection wells only make economic sense when large CO_2 flows are involved corresponding to large coal plants. Hydrogen production might be "ramped up" over time in a large fossil energy complex producing both electricity and hydrogen, with CO_2 capture-hence the National Research Council recommendation that coal-to-hydrogen production should serve as a longer-term option. Alternatively, liquid fuels might be made from coal and subsequently reformed to make hydrogen, although less carbon could be captured and sequestered in this case.

System and Feedstock Costs

Using current technology, the plant gate production cost of hydrogen via coal gasification with CO_2 capture and sequestration has been estimated to cost about $1.1/kg of hydrogen (see Table 5-7, adapted from Mitretek 2002), similar to the cost of hydrogen from natural gas. Much of the production cost is due to capital costs of the plant since coal feedstock costs are a relatively small contributor. Opportunities exist to reduce plant capital costs by improved technologies and integrated design, leading to projected lower costs in 2015. When electricity is a major co-product, hydrogen could be made at even lower costs.

Scientific and Engineering Challenges to Reduce Costs

The main challenges to reducing costs for hydrogen via coal gasification with CO_2 capture are reducing the capital cost of the process equipment, including: development of new water gas shift catalysts, new technologies for hydrogen and CO_2 separation such as membranes, and novel process technologies that combine several process steps (U.S. DOE Hydrogen from Coal Program Plan, 2004). In addition, research now underway for coal-fired electricity production is key for hydrogen from coal gasification, including RD&D on: advanced efficient coal gasification systems; advanced syngas clean-up; fuel cells or hydrogen turbines for electric co-production (DOE Hydrogen from Coal RD&D Draft Plan 2004). Finally, there are many challenges remaining in understanding the science and engineering of CO_2 sequestration (U.S. DOE Carbon Sequestration Technology Roadmap and Program Plan 2004).

Table 5-7. Production Costs

Technological Readiness	Case 1: (Current Technology)	Case 2: 2015 (Advanced Technology) H2 is Primary Output	Case 3: 2015 (Advanced Technology) Electricity is Major Co-product
Carbon Sequestration (fraction captured)	Yes (87%)	Yes (100%)	Yes (100%)
Hydrogen production (million scf/d)	119	158	153
MW H2 output HHV basis	470	630	610
tonne H_2/day	290	380	370
Coal use (tons/day) (MW)	3,000 860	3,000 860	6,000 1730
H2 FCVs served	400,000	530,000	510,000
Efficiency coal-> energy (HHV)	59	75.5	59
Excess Power (MW)	27	25	417
Power value (cents/kWh)	5.36	5.36	5.36
Capital Cost million $	417	425	950
Levelized H_2 Cost $/kg	1.10	0.79	0.54

Source: U.S. DOE Coal from Hydrogen RD&D Draft Plan 2004; Mitretek 2002.

Industry Leaders

The U.S. DOE is leading demonstration on advanced coal to hydrogen systems with CO_2 sequestration through the FutureGen program, and the Carbon Sequestration Regional Partnerships. The Carbon Capture Project (CCP), an industry working group includes many major energy and chemical companies. Companies active in coal-to-hydrogen and CO_2 sequestration include Fluor Daniel, Praxair, Alstom Power, SIMTECHE and Nexant.

California Activities and Issues

Hydrogen production from coal may have modest application in California, as relatively little of California's energy currently comes from coal, as compared to the U.S. average. In California, the West Coast Regional Carbon Sequestration Partnership, supported by the U.S. DOE and led by the California Energy Commission, plans to identify, characterize and locate CO_2 emission sources in the region and determine long-term capturing and sequestering methods by enlisting the help of numerous federal, state, local government agencies and industry sources. A list of partners is found at the U.S. DOE Website:
http://www.fe.doe.gov/programs/sequestration/partnerships/2003sel_westcoast.html RD&D Projects related to carbon sequestration in California are listed at:
http://www.fossil.energy.gov/fred/feprograms.jsp?prog=Carbon+Sequestration&state=CA

Table 5-10, which appears at the end of Section 5.3.6, summarizes hydrogen production by coal gasification.

5.3.5 Biomass Gasification

Technology Overview

Hydrogen can be produced at large scale by gasification of biomass or wastes. The feedstock is reacted with oxygen (either pure oxygen or air) and steam at high temperature producing a synthetic gas or "syngas," comprised of hydrogen, carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O) and methane (CH_4). The syngas is further processed in a water gas shift stage to increase the hydrogen content, and pure hydrogen is separated out of the mixture. Biomass-to-hydrogen routes are potentially important, because biomass is a low-cost, large resource in the United States, and in many parts of the world, especially in developing countries.

Assuming the biomass is produced renewably, there are no net carbon emissions to the atmosphere. It has been suggested that biomass hydrogen could even become a net carbon sink, if carbon dioxide is captured and sequestered. A challenge for biomass is that a relatively large amount of land is needed. Biomass hydrogen strategies must consider competing high-value uses for low-cost biomass (electricity production), land use, and environmental impacts of energy crops.

Near-Term Technologies, 2004-2010

Biomass gasifiers exist, and there has been extensive testing and demonstration of small scale biomass gasifiers (see Milne et al. 2001 for an excellent review).

Technologies Available in the 2015-2030 Timeframe

Advanced systems for biomass gasification are being investigated at NREL and at Iowa State. The U.S. DOE has set a 2015 goal of demonstrating a biomass gasifier resulting in a hydrogen cost of \$2.9/kg H_2 at the plant gate. (Devlin 2004). Current and proposed DOE annual funding levels for biomass to hydrogen RD&D are \$0.5M (FY'04); \$1.5 M is requested for FY'05 (Chalk 2004).

Scalability

As with coal gasification, biomass gasifiers are an expensive part of the system, and exhibit scale economies. This suggests that biomass gasifiers should be large, central plants. But very large biomass gasifiers would require large quantities of biomass (gathered over a wide area), which is generally expensive to store and transport long distances. With biomass there is a trade-off between lower capital costs at large plant size, and lower biomass feedstock transport costs at small plant size. The typical unit size for a biomass gasification plant is likely to be much smaller than for a coal plant, unless a large, low cost feedstock source exists nearby.

System and Feedstock Costs

The plant gate production cost of hydrogen via biomass gasification is currently about $3.6/kg of hydrogen according to U.S. DOE estimates (Spath, et al, 2000; U.S. DOE Hydrogen and Fuel Cells Multiyear Program Plan 2003). A breakdown of costs based on a conceptual design study at NREL (Spath, et al, 2000) is shown in Table 5-8. The unit size for the biomass plant is taken to be 75 tonnes per day, about 1/5th the size of a typical coal-to-hydrogen plant. Major cost factors are process equipment capital costs, especially for the gasifier, and biomass feedstock costs.

Table 5-8. NREL Cost Breakdown for Hydrogen Production by Biomass Gasification

	2003	2010 Target	2015 Target
Biomass Feedstock Cost		$42/bone dry ton	
Hydrogen production tonne H_2/day	75	75	75
Biomass use (bone dry tons/day)	1,000	1,000	1,000
H_2 FCVs served	100,000	100,000	100,000
Overall Efficiency biomass-> H_2 (LHV)	42.8%	51.3%	62.5%
Gasifier eff (LHV)	68%	75%	82%
Reformer eff	85%	89%	93%
Purification eff	74%	77%	82%
Total H_2 Plant gate Cost $/kg	3.60	2.60	2.00
Feedstock $/kg	0.8	0.6	0.5
Gasifier $/kg	1.6	1.2	1.0
Reforming $/kg	0.5	0.4	0.2
Purification $/kg	0.4	0.3	0.3

Other cost estimates for biomass gasifiers show similar costs. Simbeck and Chang (2002) estimated hydrogen plant gate cost of $2.29/kg for a 150 tonne/day hydrogen plant (twice the size of Spath et al.'s case). The National Academy of Engineering's recent report (NAE 2004) suggested that the cost of hydrogen from biomass gasification would be $4.5/kg for current technology, and $2.2/kg for future technology, for a plant producing 150 tonne/day of hydrogen.

Scientific and Engineering Challenges

As summarized in several reports by the U.S. DOE (Hydrogen Multiyear Program Plan 2003) and the IEA (Milne et al. 2001), there are ample opportunities to make technical improvements that could reduce costs of hydrogen from biomass gasification systems. Process equipment improvements include better reformer catalysts, better process heat integration, higher gasifier pressure, better feedstock handling, and improved gas clean-

up. Moreover, lower cost biomass collection, storage and transport methods could yield lower feedstock costs. As shown in the table above, the greatest improvements are projected in the capital cost of the gasifier and in lower feedstock cost contributions, because of increased efficiency of conversion in each stage. This is especially true for the gasifier where the efficiency is projected to increase from 68 percent (LHV basis) to 75 percent in 2010 and 82 percent by 2015.

Industry leaders

The U.S. DOE is leading demonstration of advanced biomass to hydrogen systems. In California, there are significant biomass resources, including forest product and agricultural wastes that might be used for hydrogen production.

Table 5-10, which appears at the end of Section 5.3.6, summarizes hydrogen production by biomass gasification.

5.3.6 High-Temperature Thermochemical Water splitting

Technology Overview

It is thermodynamically possible to split water directly into hydrogen and oxygen using heat at 4,000^{o}C, although is impractical to work at these high temperatures with current materials. However, water splitting can also be accomplished through a complex series of coupled chemical reactions driven by heat at 400 to 1,000^{o}C from nuclear reactors or solar concentrators. A number of thermochemical water splitting cycles have been investigated for use with nuclear or solar heat (Yalcin 1989). A recent assessment of nuclear hydrogen production (Brown 2002) identified the sulfur-iodine process as one of the most promising cycles. Thermochemical water splitting cycles are still undergoing research, and are not as technically mature as fossil hydrogen production systems such as steam reforming, coal gasification or water electrolysis, and should be considered a longer-term possibility.

High-temperature thermochemical cycles could use heat derived from widely available, non-carbon emitting sources such as nuclear power or solar energy to accomplish water splitting. The hope is that this would yield a lower hydrogen cost than electrolysis, which requires electricity input. As with electrolysis, the environmental and security impacts of thermochemical cycles depend on the primary source of energy (heat in this case). For example, if nuclear heat is used, there will be many of the same public safety, long-term environmental, and political issues as with nuclear electricity.

Near-Term Technologies, 2004-2010

The technology is in an early stage of development, and needs significantly more development before it can be tested for hydrogen production. Individual parts of the system have been tested, but a complete integrated system is still under development in the laboratory. The U.S. DOE Office of Nuclear Energy, Science and Technology is leading research on these systems. Current and proposed DOE Funding levels for nuclear thermochemical hydrogen RD&D: $6.4M (FY’04); $9.0 M is requested in FY’05

(Chalk 2004). Recently a project has begun to investigate using high temperature solar heat to power thermochemical cycles. DOE funding for this effort is projected to start in FY'05 at $1.25 million.

Technologies Available in the 2015-2030 timeframe

The U.S. DOE has stated a goal for 2015 of producing hydrogen via high temperature thermochemical processes with a projected cost competitive with gasoline. (Hydrogen and Fuel Cells: Multiyear Program Plan 2003). Given the nascent stage of the technology, it is unclear how long it will take to develop.

Scalability

High temperature thermochemical reactors could in theory be made at small size. If the source of heat is from nuclear reactions, the system is likely to be large scale, as nuclear technologies have strong scale economies, as well as safety and security issues favoring centralized plants. For solar-derived heat, there could be a range of sizes. Because of the early status of the technology, no optimizations for system size have been performed.

System and Feedstock Costs

It is difficult to make economic estimates for high temperature thermochemical systems with certainty, as the technology is still at the laboratory stage. The U.S. DOE has set forth what seem to be extremely ambitious goals for this technology, shown in Table 5-9 (adapted from Table 3.1.9, U.S. DOE Multiyear Program Plan 2003).

Table 5-9. DOE Goals

	2003	2005 Target	2010
High Temperature Production (700-900 ^{o}C)			
Cost at the plant $/kg	na	10	2
Energy Efficiency	na	25%	40%
Ultra High Temperature Solar Production (>1,500 ^{o}C)			
Cost at the plant $/kg	12	8	4
Solar concentrator cost $/m^2	250	130	75
Process efficiency	20%	40%	45%

Scientific and Engineering Challenges to Reduce Costs

The U.S. DOE Multiyear program plan lays out a daunting array of challenges for high-temperature thermochemical hydrogen production. These include: (1) hydrogen production from these technologies has not been proven, and components and subsystems have not been evaluated; (2) new cost-effective materials that can withstand the high temperatures and temperature cycling need to be developed; (3) there are serious public safety, environmental impact, and public acceptance issues associated with nuclear power; and (4) solar collectors are still quite expensive.

Industry leaders/California Activities

The U.S. DOE is leading demonstration of the technology through The Office of Energy Efficiency and Renewable Energy and the Office of Nuclear Science and Technology (http://www.ne.doe.gov/hydrogen/hydrogenBG.html). The University of Nevada is leading the solar experiments, and General Atomics in San Diego has been involved with the nuclear hydrogen work.

Table 5-10 summarizes hydrogen production by high-temperature water splitting.

Table 5-10. Hydrogen Production by Coal Gasification, Biomass Gasification, and High-Temperature Thermochemical Water Splitting Technologies

Production / Delivery Mode		Development Status / Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Special CA Factors	Projected Costs 2010 $/kg
Coal Gasification with CO_2 Capture and Sequestration Large, central option: not scalable (150-600 t/day H_2)	Compressed Gas or LH_2 Truck or Gas Pipeline	Coal gasification is commercial technology; CO_2 capture and sequestration demonstrations on-going; could be developed in near term	Technical barriers center on cost reduction rather than feasibility. CO_2 sequestration is still being proven via large scale demos.	Capital cost of process equipment: water gas shift catalysts, hydrogen and CO_2 separation tech (membranes), combine several process steps. Reduce cost via RD&D on: advanced efficient coal gasification systems; advanced syngas clean-up; fuel cells or hydrogen turbines for electric co-production.	Impact of CO_2 on underground storage reservoirs; need for long term monitoring to detect leaks	Coal is a relatively small part of CA's energy mix today; many CO_2 sequestration activities in CA	$0.8/kg at plant gate; $1.8/kg delivered (Note: This is U.S. DOE HPP goal for 2015)
Biomass Gasification (75-150 t/d) Midsize central option, smaller than coal H_2 systems	Compressed Gas or LH_2 Truck or Gas Pipeline	Demonstrated at pilot plant scale	Technical barriers center on cost reduction rather than feasibility	Cost reductions via process equipment improvements including better reformer catalysts, better process heat integration, higher gasifier pressure, better feedstock handling, and improved gas clean-up. Lower cost biomass collection, storage and transport methods could yield lower feedstock costs.	Land use constraints, depends on low cost biomass feedstocks	Agricultural and forest products feedstocks	$2.9/kg at plant gate (DOE 2010 goal)
High temperature Thermo-chemical H_2 Production (Nuclear) Large, central	Compressed Gas or LH_2 Truck or Gas Pipeline	Experimental, laboratory stage	Hydrogen production from these technologies has not been proven, and subsystems have not been evaluated; new cost-effective materials operating at high temperatures and temperature cycling need to be developed	Difficult to estimate costs because technology is in early stage	Same as nuclear power; serious public safety, environmental, and political issues	Research at General Atomics, UNLV	$4/kg at plant gate (DOE 2010 goal)

Production / Delivery Mode		Development Status / Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Special CA Factors	Projected Costs 2010 $/kg
Thermochemical H2 Production (Solar). Size not yet determined.	Compressed Gas or LH2 Truck or Gas Pipeline	Experimental, laboratory stage	Hydrogen production from these technologies has not been proven, and subsystems have not been evaluated; new cost-effective materials operating at high temperatures and temperature cycling need to be developed.	Difficult to estimate costs because technology is in early stage. Solar concentrating collectors expensive.	Land use for solar concentrators	Excellent solar resource	$4/kg at plant gate (DOE 2010 goal Devlin 2004)

5.3.7 Biofermentation

Direct fermentation of carbohydrate feedstocks by microorganisms is one potential, albeit far-off, technology for the production of hydrogen. While the technical feasibility has been proven, it is uncertain whether this technology can be economically competitive with gasoline or with other hydrogen production pathways. DOE studies suggest that a fermentation yield of 10 moles of hydrogen per mole of glucose and a glucose cost of 5 cents per dry pound will be required for this process to approach hydrogen costs that are competitive with gasoline. DOE has identified the grand challenges for biofermentation as:

- No known microorganism is capable of naturally producing more than 4 moles of hydrogen per mole of glucose – the metabolic pathways have not been identified and it is energetically unfavorable (and we have not discovered a mechanism to enable "reverse" electron flow to hydrogenase)
- Biomass feedstocks are too costly – need to develop low-cost methods for growing, harvesting, transporting, and pretreating energy crops and/or biomass waste products
- There is no single platform for research – a robust, industrial-capable organism that can produce greater than 4 moles of hydrogen/mole of glucose (or other sugar) has not yet been identified and validated by the research community

In order to make biofermentation a realistic hydrogen production technology, a number of scientific breakthroughs will be needed. Specifically, scientists will need to identify or genetically engineer an organism that can produce high yields of hydrogen via direct fermentation. System economics must also be improved. Low cost feedstocks must be produced using genetic engineering/breeding of crops. Better system engineering of bioreactors must be accomplished in order to lower cost. Fundamental Studies must be undertaken of complete enzymatic conversion to simplify the overall process. The current cost of hydrogen production using biofermentation is not known with certainty, but is likely more than $300/kg. It is unlikely that this cost will decrease to less than $10/kg before 2015, if not much later.

5.3.8 Membranes

Technology Overview

Hydrogen separation membranes (HSMs) are used to separate H_2 molecules from a mixed gas stream to create a permeate significantly purer in H_2 than the feedgas. Pressure Swing Absorption (PSA) is the technology used today to separate and purify H_2 but is deemed too expensive to reach DOE goals for H_2 fueling stations. Therefore, HSMs are integral to implementation of most hydrogen production technologies. HSMs can be grouped into two types of membranes, porous and dense. The types of membranes can be furthered classified into low or high temperature operating regimes. Key considerations for HSMs include hydrogen production rate, purity, cost, and durability. Production rate and purity are based on the permeation properties and the selectivity of the membranes. Both the type and operating temperature dictate the

materials of construction, selectivity, suitable gas streams, and cost. These attributes determine the most suitable application for the system incorporating them.

In porous hydrogen separation membranes (pHSMs), hydrogen is transported through the pores as molecules and the process occurs readily. The pore size of a porous membrane is tailored to discriminate between the desired species and the unwanted species. For example, a pHSM operating in a reformed fuel stream would have its microstructure tailored to allow H_2, with a molecular size of 2.89Å, to move through it while blocking other larger gases such as CO and CO_2. Selectivity is based not only molecular size but also on how the molecule moves through a medium (mean free path) and, in many instances, on the viscosity of the gas stream. Permeation rate is impacted by the thickness, tortuosity, and total porosity (pore volume) of the membrane.

Dense hydrogen separation membranes (dHSMs) are comprised of a thin, dense layer supported on a porous layer. In dHSMs, hydrogen is transported in the solid phase as hydrogen ions (protons) or as hydrogen dissolved in the dense matrix. The permeability rate of hydrogen through the dense layer is the product of the hydrogen solubility and the hydrogen diffusion rate.

Low-temperature (LT) HSMs are constructed of polymer materials and so have an operating temperature limit of approximately 100°C. The types of polymer used include polysulfone, polyimide, and tetrabromo polycarbonate with hollow fiber and spiral-wound designs.

High-temperature (HT) HSMs are comprised of inorganic materials as the operating temperatures fall between 250º and 1,000ºC and are designed to be used in harsh environments with enhanced robustness in comparison to LT-HSMs. The separation membrane in HT-pHSMs is usually made from silica and/or alumina supported by a highly porous metallic or ceramic layer. Zeolite membranes also fall in this category. HT-dHSMs are based on one of three thin (300 to 0.1 µm) membrane material types: metal, ceramic, or cermet (ceramic-metal composite). Metal HT-dHSM membranes are comprised of palladium (due the high solubility of hydrogen in palladium) on a porous ceramic support and are designed to operate between 300º and 600°C. Ceramic HT-dHSMs require materials with high protonic conductivity, high electronic conductivity and low oxygen ionic conductivity such as doped $SrCeO_3$ and doped $BaCeO_3$. In principle, both metal and ceramic HT-dHSMs can produce very high purity hydrogen because only hydrogen is transported through the membrane. Cermet HT-dHSMs are being developed to improve the mechanical, electrical, and catalytic properties with respect to pure ceramic HT-dHSMs while lowering the cost with respect to Pd-based HT-dHSMs. Along with high flux and selectivity, HT-HSMs should exhibit compatibility and stability in environments typical of the feed and permeate.

An advantage of HT-dHSMs is that their potential chemical and thermal durability makes it possible to integrate them with one of several H_2 generation technologies to create simplified, compact catalytic reformer/separator systems, called Catalytic Membrane Reactors (CMRs). To produce H_2 directly from natural gas, a CMR with a catalyst coating on the feed side is used to produce protons and electrons that are transported through a mixed-conducting dHSM to the permeate side where the protons

are reduced to H_2. Candidate membrane materials show promise but currently do not have enough electronic conductivity or environmental stability. To circumvent this issue, Praxair and Air Products are pursuing a dual membrane separator system. The first membrane separator is a natural gas/air CMR that partially oxidizes the methane into syngas (H_2 and CO). The syngas is then fed to the second membrane, a Pd alloy-based dHSM, that yields a high purity H_2 permeate. Both of these configurations will utilize catalysts for partial oxidation or auto-thermal reforming from reformer technology. A configuration that is in early development stage but has greater environmental and economic payoff is the integration of photolytic catalysts on HSMs to create efficient, inexpensive solar-to-hydrogen systems (see Photoelectrochemical discussion in Section 5.3.3). Though LT-HSMs could be used for these systems, thermal, chemical, and UV stability demands will likely drive them towards to ceramic HT-HSMs.

Technical Barriers

In order to fully exploit the unique capabilities of the HT-HSMs, they must be sealed to a dense ceramic or a metal support structure. Commonly used seals are not suitable for these applications because their heat resistance is ineffective above 400ºC and their sealing processes require higher yields. Additionally, HT-pHSMs suffer from loss of porosity at high temperatures. For HT-dHSMs, the focus is on decreasing the Pd content for metal and cermet membranes while increasing the stability and electronic conductivity of mixed ionic and electronic conducting (MIEC) materials. Additionally, cost-effective methods for fabricating the thin-film membranes on the porous supports are essential to the commercialization of HT-HSMs. LT-HSMs are susceptible to fouling from higher hydrocarbon and sulfur contaminants in natural gas feeds. Furthermore, they do not operate well under dynamic conditions likely to be encountered in a H_2-fueling station. However, they may be the most suitable approach for H_2-O_2 separation in tandem with photolysis systems. A large component of cost in any of these systems is the compressor for the H_2 permeate. Therefore, system designs amenable to producing compressed permeate with any type of membrane are needed.

Cost

System construction entails forming the membranes into modules which are then incorporated into a system. In LT-HSMs, the membrane module selling price at high volume is in the range of \$30 to 300/m^2 for present technology and projected to be \$6 to 15/m^2 for advanced membrane designs. These prices are 2 to 3 times the module production cost. The module production cost is 10 to 25 percent of the total system cost. Whether a complete or partial system would be required for a particular H_2 fueling station application will depend on the H_2 generation technology it is mated with. The 2010 targets for Pd-based membranes are significantly higher, on the order of \$1,000/m^2. At the target flux of 200 scfh/ft^2, this translates to a capital cost of approximately \$14,000 for a membrane capable of producing 500 kg of H_2 per day. Durability goals for these membranes are 100,000 hours. Such a system would have to be mated to a H_2 storage subsystem. An on-demand H_2 production system will require either an order of magnitude larger flux or lower cost.

Technologies Available Now/By 2010

The first large-scale applications of HSMs was for ammonia purge gas streams and adjusting H_2:CO ratio in syngas plants. These systems are comprised of LT-HSMs. Current suitability of LT-HSM technology for separating O_2-H_2 streams from photolytic generation schemes is unknown. However, the maturity of LT-HSM systems make them an attractive option to pursue as photolytic generation comes closer to reality.

Regulatory, crude quality, and economic factors are driving the increasing demand for increased H_2 usage in refineries. Many of the gas streams in refineries are 30 to 80 percent hydrogen mixed with light hydrocarbons making them ideal for HSM systems. This, plus present applications are expected to create a $90M market in 2010.

HT-HSMs are under development to separate H_2 generated during combustion of natural gas, coal, and other fossil fuels from the product stream. In addition to potentially using HT-HSMs to reform natural gas on site, HT-HSMs are critical supporting technologies for next generation power systems under development in DOE's Vision 21, Clean Coal, and FutureGen efforts. The H_2-depleted residue gas is then directed to units that separate and sequester CO_2, CO, and particulates. The combined driving forces of refinery and next generation power system applications creates a high probability that Pd-based HT-HSMs will be available by 2010 to separate H_2 generated by both on-site and centralized natural gas reforming, though a H_2 storage system will likely also be required. It is likely that the cost of hydrogen produced by these systems could be competitive with gasoline by 2015.

Technologies Potentially Available in the 2015-2030

The availability of dual membrane HT-HSM systems for direct H_2 generation via natural gas reforming is plausible for the 2015 timeframe. Though the potential exists for on-demand systems, the high operating temperatures will likely make continuous production most economical, creating the necessity for a H_2 storage subsystem.

Thermal water splitting systems will need to utilize HT-HSMs due to the use of corrosive materials, such as sulfuric acid, hydrohalic acids, and water, at high temperatures (750º to 900°C). However, it appears a significant amount of materials development is needed to achieve durability requirements for this application.

5.4 Delivery Options

For hydrogen infrastructure options that involve central production (i.e., other than onsite production at the fueling station, which is also referred to as forecourt production), the hydrogen must be delivered to the station from the production plant. Therefore, hydrogen delivery technologies are considered as part of this hydrogen production and distribution evaluation. There are numerous cost tradeoffs in comparing centralized (reforming) hydrogen production with truck delivery to forecourt reforming production. We do not explicitly give a side-by-side comparison here, instead the reader is directed to the National Academies report: "The Hydrogen Economy:

Opportunities, Costs, Barriers, and R&D Needs," which is available on the DOE website for more detailed information.

Hydrogen can be delivered as a compressed gas or cryogenic liquid. The compressed gas can be transported in a pipeline or in pressure vessels, which are typically transported over highways in so-called tube trailers. Liquid hydrogen is routinely transported over highways in tank trucks, although rail or barge transportation is also feasible. Liquid hydrogen pipelines longer than a few tens of meters are impractical due to heat transfer and vaporization.

DOE HFCIT has an active hydrogen pipeline R&D program. This research is investigating issues such as new pipeline technologies and costs, the feasibility of converting natural gas pipelines to hydrogen, and the possibility of pipeline transportation of hydrogen mixed with natural gas. While these technologies are promising with regard to potential future central plant hydrogen production and distribution scenarios, they will probably not be fielded before 2010. There are a few existing highly localized hydrogen pipelines connecting production plants to petroleum refineries. Under DOE and SCAQMD sponsorship, APCI plans to install a hydrogen fueling station supplied by their pipeline in the Torrance, California area. However, there are very few of these existing hydrogen pipelines, and so we have not considered them to be a general hydrogen delivery option. Similarly, we categorize purpose-built hydrogen fueling station supply pipelines as a post-2010 option.

For Phase I, we consider three hydrogen delivery options: tube trailers, cryogenic tank trucks, and mobile fueling units. Pertinent information regarding these options is listed in the accompanying table. More detailed information is availed in the listed references. Mobile hydrogen fueling stations are considered here because most (but not all) mobile fuelers are refilled at central production plants.

Hydrogen delivery is potentially an important element of the California Hydrogen Highway Blueprint for two reasons:

1. In the longer term, if central production of hydrogen emerges to be more attractive than distributed production (in terms of societal benefits and economics), then delivery from the production plant to the fueling station is obviously required.

2. In the very near term, an excess supply of merchant hydrogen is available from existing hydrogen plants in California. Therefore, tube trailer or tank truck delivery, or use of mobile fueling units, may provide a low initial-cost option for providing fuel for hydrogen vehicles while other options with better societal benefits and life-cycle costs are being developed.

As indicated in Table 5-11, tube trailers typically hold roughly 120,000 scf (280 kg) of hydrogen at 2,400 to 3,100 psi. Tube trailers are usually leased (with a refill and delivery charge) from industrial gas companies, but they can also be purchased. A station utilizing a tube trailer has both simplifications and special requirements. Obviously, no hydrogen production or purification equipment is needed. On the other hand, a large area is needed for a truck to exchange the trailers. Also, in order to utilize a substantial

fraction of the trailer capacity, a compressor and downstream pressure vessel cascade or buffer is needed. As a practical matter, because commonly used reciprocating compressors operate with a relatively inflexible pressure ratio, a pressure regulator is usually used between the trailer and compressor, which decreases efficiency and increases costs. On the other hand, a smaller pressure vessel cascade can be used compared to an equivalent-capacity onsite production station.

Tube trailers use DOT pressure vessels, and some jurisdictions prefer or require ASME pressure vessels for permanent installations. This may lead to permitting challenges if tube trailers are parked for long periods at hydrogen fueling stations used by the general public.

Cryogenic tank trucks hold from 10,000 to 17,000 gallons (approximately 2,600 to 4,400 kg) of hydrogen, as indicated in Table 5-11. The tanks are vacuum-jacketed to provide the needed thermal insulation, and their construction conforms with DOT regulations. Cryogenic tank trucks deliver liquid hydrogen into a cryogenic tank at the fueling station. The basic infrastructure is analogous to gasoline and diesel fuel delivery and storage.

Liquid hydrogen delivery and storage is best suited to fueling stations with substantial and regular throughput, because this minimizes or eliminates boil-off losses. Also, for these stations, a liquid pump can replace the gas compressor. This reduces capital and operating costs, and it enables high-rate (kg/min) hydrogen dispensing with minimal cascade or buffer gas storage capacity. The economics of liquid or gaseous hydrogen delivery improve when the station is near the hydrogen plant.

The term “mobile hydrogen fueling station” covers a variety of devices, including:

- A trailer consisting of a pressure vessel cascade, dispenser, controls, and safety equipment — The cascade must be refilled frequently and/or vehicles cannot be refueled to maximum pressures

- A trailer consisting of pressure vessels, a compressor, a small downstream pressure vessel cascade, dispenser, controls, and safety equipment — This system can use most of the stored hydrogen, but it is more complex and expensive

- A trailer consisting of a compressor, downstream cascade, dispenser, controls, and safety equipment — This trailer connects to a hydrogen supply such as a tube trailer or pack of bottles

- A small trailer-mounted electrolyzer, purification equipment, compressor, cascade, dispenser, controls, and safety equipment — This trailer connects to electric and water service, and it does not need to be refilled at a central plant

Details regarding these mobile fueler alternatives are provided in the listed in Section 5.6, Bibliography. Experience to date shows that permitting mobile fueler applications can be just as involved as permitting a permanent hydrogen fueling station installation.

Table 5-11. Hydrogen Delivery Options

Delivery Option	Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
(a) Liquid Hydrogen Cryogenic Tank Trucks	Liquid hydrogen tank trucks (a tank semi-trailer and a Class 8 tractor) can transport hydrogen from a central production plant to refueling stations with liquid hydrogen storage tanks. This infrastructure scenario is analogous to gasoline and diesel fuel production and distribution. The capacity of current liquid hydrogen trucks ranges from 10,000 to 17,000 gallons (Approx. 2,600 to 4,400 kg). Liquid hydrogen is stored at approximately –420°F in a vacuum-jacketed tank.	Highway transportation of liquid hydrogen in tank trucks is an established commercial technology. There are no technical barriers and no R&D investment is required. Trucks and their operation are regulated by DOT and state codes. Their safety record is excellent. Liquid hydrogen delivery is appropriate only to stations that store liquid hydrogen, and these stations are not well suited to applications with lengthy idle periods (due to product boil-off loss).	Currently, liquid hydrogen tank trucks are owned and operated by central-plant hydrogen producers. There is no initial capital investment required. Hydrogen purchase contracts can be per delivered kg. Alternatively, liquid hydrogen delivery costs can be estimated as $0.001 to 0.003 per kg-mile (one way full truck delivery). Note that liquid delivery and storage can reduce station cost (pumps are cheaper than compressors and minimal high-pressure storage is required) and enable high dispensing rates. Boil off losses must be minimized to keep costs acceptable.	Liquid hydrogen truck delivery requires central plant production and liquefaction. Current central plant production is via SMR, which consumes natural gas and emits substantial greenhouse gas and some criteria pollutants. Current liquefiers have motor-driven compressors, and the associated grid-electricity generation emissions and resource consumption, although these are lower than those associated with electrolysis. The diesel truck also produces NO_x, PM, and greenhouse gases.	A 15,000 gallon liquid hydrogen cryogenic trailer costs approximately $500k. Liquid hydrogen tank trucks are a mature technology, and significant cost reductions associated with technology improvements are unlikely. Minor economies of scale may be realized if more tank trucks are built and operated. DOE plans R&D to increase hydrogen liquefaction efficiency and hence reduce cost.

Delivery Option	Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
(b) Compressed hydrogen tube trailers	Hydrogen can be transported from a central production plant and stored at a fueling station site in compressed hydrogen tube trailers. A tube trailer consists of a pack of connected cylinders mounted on a semi-trailer that is transported by a tractor. Tube trailers are typically exchanged at the customer's site. Tube trailers have different capacities, but 120,000 scf (280 kg) at 2,400 to 3,100 psi is typical. DOT regulations apply to tube trailers traveling on highways, but state or local regulations may apply to tube trailers installed at stations.	Highway transportation of compressed hydrogen in tube trailers is an established commercial technology. There are no technical barriers and no R&D investment is required. Their safety record is excellent. Hydrogen may be delivered to and stored at fueling stations designed to accept hydrogen from tube trail trailers. A compressor is needed for efficient use of the hydrogen in the tube trailer (80-90%). Most compressors need a constant suction pressure, which requires a pressure regulator between the tube trailer and compressor.	A tractor transporting a tube trailer will consume energy equivalent to all the energy in the tube trailer if the delivery is longer than roughly 500 miles. Therefore, tube trailer delivery is not an economically viable long-term strategy if the station is not very near to the production plant. However, tube trailers can be leased, and therefore this option may be attractive for initial or temporary applications where initial capital costs are more important than life cycle costs.	Tube trailer hydrogen delivery requires central plant production and compression (usually accomplished by liquefaction, pumping, and vaporizing). Current central plant production is via SMR, which consumes natural gas and emits substantial greenhouse gas and some criteria pollutants. Current liquefiers have motor-driven compressors, and the associated grid-electricity generation emissions and resource consumption, although these are lower than those associated with electrolysis. The diesel truck also produces NO_x, PM, and greenhouse gases.	A 120,000 scf compressed hydrogen tube trailer costs approximately $140k. Compressed hydrogen tube trailers are a mature technology, and substantial cost reductions associated with technology improvements are unlikely. Minor economies of scale may be realized if more tube trailers are built and operated. Also, ongoing DOE compressed hydrogen storage technology R&D programs (which are targeted primarily to on-vehicle storage) may be partially applicable to tube trailers.

Delivery Option	Development Status/Industry Readiness	Technical Barriers	Economic Barriers	Environmental Considerations	Projected Cost in 2010
(c) Mobile hydrogen fueling stations	Various types of mobile hydrogen fueling units are available. The simplest is basically a compressed hydrogen pressure vessel cascade plus dispensing equipment on wheels. A compressor can be added to increase the usable hydrogen fraction, but this substantially increases complexity and cost. These compressed hydrogen mobile units are refilled at a central production plant or a permanent fueling station. Mobile electrolyzer fueling stations are also available. These require water and substantial electric service, but they do not need to be refilled at a production plant.	While there are no technical barriers to mobile hydrogen fueling units, they are inefficient with respect to % usable hydrogen (i.e., very few cars can be refueled to maximum capacity) unless they include a compressor (which makes them much more complex and expensive). Also, different codes and regulations apply to hydrogen transportation and stationary applications, and this creates permitting problems.	Mobile fuelers can be leased. Therefore they have low or zero initial capital cost, but they have extremely high cost measured as $/kg for long-term use. Therefore, mobile hydrogen fueling units are used to fulfill temporary requirements such as refueling before a permanent station installation is complete, limited-time demonstrations, and hydrogen vehicle events that are not near existing stations.	The environmental considerations associated with mobile hydrogen fueling unit use is similar to tube trailer use (above), except that it is worse because more highway travel is required per kg of hydrogen dispensed.	Current lease rates for a 162 kg (120 kg usable), 5,000-psi mobile hydrogen fueling units are significant. These rates may decrease in the future if usage increases and mobile hydrogen fueler leasing becomes more competitive. Capital costs of mobile hydrogen fuelers may decrease as a result of DOE hydrogen storage R&D and/or increased pressure vessel production volumes.

However, mobile hydrogen fuelers may be a low-cost near-term option for providing temporary refueling capabilities, for hydrogen vehicles in California.

5.5 Recommendations

There are a number of important goals we want to achieve by developing hydrogen production and delivery technologies for the California Hydrogen Highways. These are: increasing energy security through reductions in foreign oil imports; improvement of the environment; and to enhance the economic competitiveness of the U. S. and California economic competitiveness. It is fortuitous that the use of hydrogen as a fuel in transportation will allow us to accomplish all three goals. Indeed, the argument to move to a hydrogen economy has to be made both because of its energy security and beneficial environmental aspects. There are important economic benefits to be gained through the commercialization of the hydrogen production and delivery technologies discussed in this report. First, numerous jobs will be created in the hydrogen industry in California. Secondly, these technologies will be exportable, not only producing financial gains for companies doing business in California but also improving the environment beyond California's borders. We will approach the work outlined in this report in phases. Our general recommendations to be carried forward throughout the development of the hydrogen infrastructure are presented below. These are followed by a discussion of specific recommendations for Phase I, II, and III.

5.5.1 General Recommendations

<u>Start now with a mix of production options that, to the greatest extent possible given technology and cost constraints, reflect the diversity of production options and the long-term goals of the CA H2 Net highway effort.</u>

For the purposes of developing the transitional CA H2 Net, the State should utilize a diverse spectrum of hydrogen production options that leverages those technologies for hydrogen production and delivery that are available today, or most likely to be available in the 2005-2010 timeframe. In addition it will be essential to include hydrogen production pathways that are likely to be needed in the future to ensure that California continues to move towards energy independence. In specific locales (e.g., Torrance), delivery through pipeline will play a role. Mobile refuelers can also be utilized. The DOE 2015 dispensed hydrogen cost goals ($2.85/kg for electrolysis and $1.50/kg for steam methane reforming (SMR)) are unlikely to be met by 2010. Therefore, we should not anticipate that hydrogen will be able to compete with gasoline in terms of cost on a per-gallon energy equivalent basis. In addition, the use of hydrogen as a fuel does not necessarily help solve pollution or greenhouse gas inventory problems in the near term. Indeed, electrolysis using electricity from the grid and SMR are not emission-free technologies unless CO_2 capture and sequestration are developed. Electrolysis from renewable resources (e.g., wind) is an emission-free process; however, this production pathway can only be utilized to a limited extent in the near-term.

Build consumer knowledge and gain acceptance of new technologies

Nearer-term consumer acceptance would need to be obtained based on demonstration of these technologies. One of the best ways to accomplish this is for consumers to personally experience the new technology via a ride on a transit bus, hands-on refueling, visit to Hydrogen Power Parks, or through other education and outreach activities planned under the various fleet demonstrations to be conducted in California through Industry/Government partnerships.

Leverage the synergy between the SCAQMD and DOE demonstrations

Significant activities are planned for the next five years in the State of California. Explicit mechanisms should be put in place, such as have begun under the early stages of the EO implementation planning, to ensure the State gains full advantage from the separate efforts and vice versa.

Develop hydrogen from renewable resources

In the time period beyond 2010 we anticipate that other technologies for hydrogen production will become technically viable, and could become economically viable. These “farther out” technologies include photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass and coal, high temperature thermochemical, and catalytic membranes. The DOE is sponsoring research aimed at advancing these technologies. The State may also wish to sponsor R&D in this area to explore any early opportunities to demonstrate and utilize hydrogen production from these pathways. In particular, centralized biomass gasification and wind-powered electrolysis can potentially have a larger impact in specific regions of California during the time period between now and 2010.

Promote the use of hydrogen in non-transportation applications

Hydrogen production technology development can be advanced through expanded societal use of hydrogen. This will enhance the case for a market for hydrogen leading to increased private sector investment. The use of hydrogen as an energy storage medium and in fuels cells for stationary power should be promoted.

Approach the transition in phases

The State of California can accelerate the development of hydrogen production and delivery technology options within our borders. Three phases of activities are envisioned: Phase I (now-2010), Phase II (2010-2015), and Phase III (beyond 2015). Some specific recommendations for these time periods are given below. These programs should be guided by an ongoing and balanced assessment of hydrogen versus other alternatives to achieve California’s emissions, economic, and business climate goals.

5.5.2 Specific Recommendations for Phase I, II, and III

Phase I (now-2010): The Early Transition Period-Demonstrations, Technology Evaluation and Advancement, and Collaboration with Federal Programs

State funding should be provided for collaborative demonstration production projects involving private industry, universities, and California national laboratories. These demonstration projects should be done in collaboration/coordination with the existing and planned DOE infrastructure and fleet demonstration projects to best leverage resources. Obviously, emphasis should be given to co-locating distributed hydrogen production demonstration technology at sites where FCV and hydrogen ICEV demonstrations/fleets are to be placed. Demonstration of reduced hydrogen costs and scalability for SMR and electrolysis should be priorities. In the early transition years, distributed production facilities with capacities of 50 to 250 kg hydrogen per day are the target. Emphasis should be give on the development of prototype designs for distributed production that can be commercialized in the following years.

1. In coordination with federal funding, utilize PIER funding for fundamental and applied R&D at California national laboratories and universities. Again, this work should be coordinated with the DOE program and used to fund promising technologies that might be under funded due to earmarking of the DOE budget or other constraints. The work should be focused on technologies that can exploit resources available in California. The major part of this funding should be directed towards technology development that could have an impact in the next 5 to 7 years. That is, additional funding should be provided for the development of those distributed production technologies that show current promise for ultimate wide scale deployment. This implies mass production and commercialization of units that can produce hydrogen at costs meeting or approaching DOE targets. Specific technologies include fuel reforming and electrolysis. In the area of advanced electrolysis, specific emphasis should concentrate on increasing system efficiency, lower cost materials and components, high pressure operation, and improved materials and system durability and reliability. Integration of electrolysis systems with wind and solar should also be addressed. Because they offer the promise of highest efficiency, the development of solid oxide electrolyzers (SOEs) should receive concentration.

   In the area of fuels reforming (specifically SMR), emphasis should again be directed towards solving technical hurdles that will allow cost reductions and improve systems reliability and durability. Specifically, improvements in reactor materials and development of lower cost, higher activity catalysts are important. Demonstration of scalability (to smaller size systems in the 50 to 250 kg/day range) should also be given attention. Co-production of hydrogen and electricity, as a way of reducing overall hydrogen costs, should be considered and further developed for applications where this option is economically justified.

   Support should also be provided, albeit at less concentrated levels, for the development of the “farther out” production technologies. These technologies are not expected to play a significant role in hydrogen production until well after 2010. They include photobiological and photoelectrochemical, biofermentation, pyrolysis

and gasification of biomass (particularly the smaller-scale distributed option), high temperature thermochemical, and catalytic membranes. Fundamental research on photobiological hydrogen production would make use the outstanding bioengineering centers available in California universities and national labs. There are many groups within California investigating photoelectrochemical hydrogen research. The primary goal of work in these areas should be to attack the technical hurdles to higher efficiency and lower cost for hydrogen production using these processes.

2. Truck delivery to rural areas and smaller cities should be the principal method of providing hydrogen in the transitional period. Also, in more remote rural areas, where natural gas pipelines are lacking, consideration should also be given to reforming of liquid fuels such as methanol and ethanol, as a truck distribution infrastructure for these energy carriers already exists.

3. Encouragement should be given to co-production of hydrogen (though electrolysis) at existing and planned wind and solar power sites. System integration and optimization issues need to be resolved and high efficiency under variable electrolyzer input conditions needs to be demonstrated.

4. While focusing on the development of Hydrogen Highways, the use of hydrogen and fuel cells should be promoted in stationary power production. The development of Hydrogen Power Parks should be encouraged with the public invited in as part of the public outreach/education campaign. These parks would not only be used for hydrogen refueling of vehicles but also for electricity generation in fuel cells. The Hydrogen Power Parks should function as demonstration sites for a variety of distributed hydrogen production technology options that show promise for economic and commercial viability.

5. The State should look for an early site to demonstrate the biomass production route for hydrogen, as well as ethanol and methanol from which hydrogen can be derived, given the strong synergy with resources in the State. Although the technology is further away, there may be a unique opportunity to begin the longer development curve.

6. The Hydrogen Highways Initiative should work with DOE in establishing appropriate safety, codes and standards for hydrogen production and use. Hydrogen purity requirements and refueling protocols are particular areas of interest.

<u>Phase II (2010-2015): Implement Expanded Production Infrastructure — The Verge of Commercialization for FCVs and Expanded Stationary Power Uses</u>

1. These years could see greatly expanded numbers of hydrogen ICEVs and FCVs (the latter still principally in fleet demonstrations) on California roads, advancing the case for mass production (commercialization) of FCVs. If these greatly increased numbers materialize, and consistent with hydrogen fuel demand, expanded distributed production infrastructure should accompany this increase. Depending on need, more refueling stations will need to be developed along highways and in rural

areas utilizing the resources (feedstocks) most readily available in those areas, taking into consideration the economic factors involved. The use of fuel cells and hydrogen fuel in stationary power applications should also be expanded.

2. Demonstrations of wider scalability for SMR and electrolysis should be done. For these technologies, demonstrate that it is possible to achieve DOE hydrogen cost targets of $1.50/kg for SMR and $2.85/kg for electrolysis. If achievement of these cost targets can be demonstrated and there is sufficient hydrogen demand for high station utilization, distributed station production capacities in the 250 to 1,500 kg/day range should be demonstrated and deployed, particularly for SMR.

3. Advanced production technologies should continue to be developed through PIER program in conjunction with federal funding, and in partnership with the private sector. As technical hurdles are overcome and the case is made for commercialization, funding for SMR research should ramp down during this time period. Funding for advanced electrolysis research, particularly solid oxide electrolyzers (SOEs), should continue if there is a clear and economic commercialization pathway for this technology. There are more technical and economic hurdles for electrolysis using SOEs to overcome before the commercial case can be made for mass production. Early in this time period, the emphasis on SOEs should be directed towards the demonstration of prototypes with capacities in the 10 to 100 kg/day range. However, mass production of alkaline and PEM electrolyzer units in varying sizes can begin in this time period. Funding should be increased for the “farther out” production technologies of photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass, high temperature thermochemical, and catalytic membranes. This funding should be contingent on successful research results indicating that it is possible to overcome scientific and engineering hurdles for these technologies so that the DOE 2015 hydrogen cost targets can be reached. During this time period, a down-selection process should be initiated to identify the most promising technologies in which to concentrate funding. This should be done in coordination with the DOE program, which will be investing significant resources into the development of all of these production methods.

4. Demonstrate commercial viability for co-production (electricity and hydrogen) Hydrogen Power Parks.

5. Optimize production and utilization of hydrogen as an energy carrier (energy storage medium) to facilitate the utilization of intermittent renewable sources of wind and solar. Compare economic viability with other means of integrating these intermittent resources, both with the grid and in stand-alone applications.

6. Poll public as to willingness to buy FCVs/H2 ICEVs and use hydrogen and use this information in establishing regional production options/station siting.

<u>Phase III (beyond 2015): Full Implementation of the California Hydrogen Highways and the Extended Hydrogen Economy</u>

1. In 2015 the automobile OEMs have stated that they will make decisions regarding mass production of FCVs. Hydrogen production will continue to rely heavily on fossil sources (e.g., SMR) although “carbon-free” hydrogen production options will continue to gain economic competitiveness. If the OEMs make a positive mass production decision and it is clear that the cars will be coming, the State should continue to encourage those advanced technologies that show promise for eventual commercialization in the years beyond 2015, concentrating funding in the down-selected technologies. Commercialization for these technologies should begin in the 2015-2030 timeframe. Production scenarios should rely on an optimized regional mix of technologies including renewable resources, and fossil-based that provide both environmental and economic benefits. Both centralized and distributed production should be utilized. Analytical models should be utilized to optimize the electricity grid/hydrogen production capacities for maximum efficiency, lowest emissions, and lowest cost to consumer. With appropriate technology and if extremely strong customer support materializes, mostly “carbon-free” hydrogen production system could be achieved before 2050.

2. Consider hydrogen pipeline infrastructure within California for hydrogen delivery from centralized or sub-station production facilities. This should be complete by 2050. By then, the transition to a hydrogen economy in California can be accomplished.

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Table 5-12. Biological Hydrogen Production

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6. Siting of Hydrogen Fueling Stations

6.1 Overview and Purpose

Successful deployment of hydrogen vehicles in California requires a network of hydrogen fueling stations to be placed in strategic locations enabling regional (inter-city), inter-regional, and ultimately inter-state travel. The Rollout Strategy Topic Team established the Sites subgroup to develop the site identification process.

The purpose of this section is to guide the selection for new hydrogen fueling station and distributed generation sites in California. In determining the sites, this section does not direct the type of station or form of fuel (liquid, low or high pressure hydrogen, HCNG, etc.) to be installed but rather only seeks to provide a process to determine site host locations and partners. Several criteria have been established to screen candidate site locations and to guide final site selections, including site host commitment, economics, station utilization, and long-term implementation planning.

To develop the network of hydrogen stations, strategies as well as obstacles and barriers are considered. Ultimately, the implementation plan provides direction on refining network site opportunities along with State initiatives that will facilitate and hasten the creation of the California Hydrogen Highway.

6.2 Goals

The Sites subgroup identified three primary goals for hydrogen fuel station placement. The first goal was to maximize network development and reliability. The focus of this goal was to establish regional clusters of stations, then identify “bridging” station locations between regions with the ultimate purpose to enable inter-state travel.

The second goal was to maximize the number of stations accessible to the maximum number of consumers. These stations should be convenient for commercial and government fleets as well as the individual consumer. Greater consumer access will permit full commercialization of hydrogen fuel vehicles for public use.

The third goal was to ensure that each location operate with a high percentage of fuel utilization demonstrating maximum hydrogen fuel throughput. This will ensure early return on investment and encourage the construction of additional stations.

6.3 Siting Strategy

The rollout of hydrogen vehicles in the marketplace must be accompanied by the rollout of the hydrogen fueling infrastructure. These actions must be planned and executed in concert in order to effectively establish a commercial hydrogen transportation business. Hence, the commercialization plan must be well communicated such that the initial hydrogen station siting efforts will support the long term commercialization plans to the

greatest extent possible, while serving the near-term needs for flexibility and shared risk.

The siting criteria outlined here are strategies for implementing stations, starting from broad programmatic support, to specific siting questions and policy actions. Although many of these issues are discussed in other Topic Teams, these issues are clearly hydrogen station siting *requirements* and were thus included here to provide a comprehensive analysis.

6.3.1 Facilitating the Initial Station Network

The initial fueling network must be developed through public-private partnerships with industry and the State of California, Department of Energy (DOE) and local air districts. The challenges of these initial demonstrations are:

1. Only smaller capacity stations demonstrating a variety of technologies will be implemented. For longer term network development and commercialization, high capacity “gasoline” like stations and/or home refueling stations will be required.

2. To accelerate network development, it is critical that development experience and information from these initial demonstrations be quickly gathered and communicated to establish critical station criteria regarding fueling pressure and reliability.

The initial network will be based on demonstration technologies that are continually being improved. As a result, these stations will most likely require substantial replacement and upgrade investment within seven to ten years depending upon vehicle availability and network demand. As vehicle deployment and demand grow, public-private partnerships must consider a continuation of the process and determine when the market can be self-sustaining.

Siting of new hydrogen stations will require public resources, such as establishing the codes and standards for station siting (see Implementation Topic Team Report), incentives for hydrogen vehicle utilization (see Economics Topic Team Report), emergency response capabilities (see Implementation Topic Team Report), and training (see Public Education Topic Team Report). Working with commercial companies to the extent that new station sites will augment or accelerate the hydrogen business plans within the state of California is essential.

6.3.2 Establishing the Initial Station Network

Fleets and Clustering

Initially, regional networks (or clusters) providing public access are to be targeted for development. Regional networks are to be targeted in San Diego, the greater Los Angeles, Sacramento, San Francisco, and San Joaquin areas. The methods and criteria for screening and selecting new station sites must facilitate short-term regional development, while supporting long=term efforts to bring hydrogen transportation to the commercial marketplace.

In the short-term and mid-term scenarios, finding host site partners facilitating station development is critical. The target hosts and criteria presented in this document provide the foundation to leverage and create development of a gaseous fuels station network. Target locations within each region should consider the “Anchor Tenant” model. This model requires that the “host tenant” has a demand (either vehicles or distributed generation) for hydrogen, thereby serving as the anchor or base-load for the station. This demand will dictate the size and possibly the type of station (mobile, delivered, on-site production). Until automakers have commercial consumer vehicles available and the fuel price is competitive or better than gasoline or diesel, a “build it and they will come” strategy is not feasible, nor realistic.

However, between now and when retail vehicles are available, broadening public acceptance and awareness of gaseous fuels is essential (see Societal Benefits Inclusivity document). Consistent efforts of opening hydrogen, HCNG, and natural gas fueling stations will create consumer confidence and automaker commitment facilitating transition to the hydrogen only economy.

One strategy to encourage production in the early stages is to engage State and Municipal Fleets, as well as those fleets providing public service (transit, street-sweeping, refuse, etc.), to serve as anchors and offer public access to support broader commercialization. Maximizing the use of government sites for station placement can also leverage immediate experience with alternative fuel vehicle programs such as natural gas. These fleets may have the initiative and available real estate for new hydrogen stations in addition to existing natural gas stations. Placing stations at government sites could also help leverage agency funding. Agency fleets to be considered should ensure cooperation with other local fleets and arrange for public access to the maximum extent possible.

For long-term network development, when vehicles are commercially available to the public and competitively priced in all facets, broad retail gasoline station network co-location becomes feasible.

Leveraging

There is an existing network of natural gas fueling stations that should also be leveraged for siting hydrogen and HCNG stations that can support establishing the initial fueling network.

A balance between on-site production (various types), delivered, and mobile fueling stations should be initially developed. A potential station technology mix is presented in more detail within the Societal Benefits Topic Team report.

The existing hydrogen fueling infrastructure demonstrations planned by the Department of Energy should also be incorporated in the CA H2 Net. This program is funding automaker / energy company demonstrations in California. Disclosure and inclusion of these infrastructure plans is essential to support creation of the initial regional networks. Similarly, there have been significant resources already invested in the California hydrogen infrastructure by the South Coast AQMD and others, and those sites should

be assessed for “lessons learned.” These stations should also be analyzed for their utility as individual stations and for the opportunity to network with new stations within the regional and eventually statewide network.

Effective site selection strategy will identify new hydrogen fueling sites that will be used in the near-term and remain as permanent fueling site locations in the future, thus helping to justify initial investments

6.4 Obstacles to Developing Network Sites

The Sites subgroup identified several potential barriers that should be addressed in an effort to implement a network of hydrogen fueling stations within California. Chief among these obstacles are:

6.4.1 Insurance Challenges

Most safety experts agree that with proper handling hydrogen is a safe fuel, and in some instances, safer than traditional fuels such as gasoline and diesel. However, lack of broad experience with the handling of hydrogen, particularly in fueling station or power generation applications serve to exacerbate concerns within the insurance industry.

Risks involve hydrogen’s wide flammability range, low activation energy, and being unsuitable for adding odorants. These properties, combined with the general public’s recollection of the Hindenburg tragedy (which we now know was caused by the ignition of the airship’s skin and not by hydrogen contained within the airship), create a negative perception of the fuel. These qualities transcend to the insurance marketplace and require a higher level of expertise in educating underwriters. Generally speaking, insurance carriers for specialty markets, such as hydrogen projects, are limited and require a targeted educational program to overcome these perceptions and concerns.

Actuarial / Underwriting Data

Hydrogen has been used widely in the metals fabrication, float glass, semiconductor, refining, and food industries for decades with an excellent safety record. Additionally, through more than five years of hydrogen vehicle refueling activities at the California Fuel Cell Partnership, as well as other hydrogen fueling installations throughout the U.S., Europe, and Japan, a fairly substantial database of safe hydrogen fueling events has emerged. Our challenge is to educate key stakeholders including the insurance underwriting community, as well as the executive, legislative, and judicial branches of government, potential fueling station landlords, and the public at large about hydrogen’s safe characteristics (such as its extremely low specific gravity, high diffusion rate, and low lateral radiant heat energy) so we can continue the development in California of an early hydrogen fueling station network.

Safety experts widely agree that the use of hydrogen as a transportation fuel will not pose greater dangers to the general public than does the current use of petroleum-based fuels. One source of claims experience is establishing that hydrogen vehicle

accident claims are to be treated by the courts in much the same way that energy companies, the corner gasoline station, and the general public have experienced with gasoline. For example, liabilities for accidents arising out of the use of a hydrogen vehicle involving damages to persons or property should be relegated to areas where the fuel provider has control to transfer the risks, where possible or legally enforceable. Gasoline station owners are not, for example, held liable in U.S. torts system in a claim involving third party vehicle injuries caused by spilled gasoline igniting. This is primarily due to the perception that it is common knowledge of the general public that gasoline contains energy and without proper and safe handling can be potentially dangerous. Hydrogen as a transportation fuel should be viewed in the same manner as traditional fuels, whereby its providers can transfer the risks involving hydrogen powered vehicles that are not directly under the control of the hydrogen fuel provider.

"To address liability insurance companies have two ways of looking at risk; 1) private safety is based on probabilities; 2) public safety is based on possibilities" [45]. It should also be noted that insurance companies, when calculating risk, rely heavily upon first responder evaluations of safety regarding property and lives. This also highlights the fact that there has to be an intense educational and training program for new and existing first responders such as fire fighters and emergency medical technicians (EMTs) regarding the properties of hydrogen, fuel cells and hydrogen ICEs. Until this occurs can we expect their full support for this technology being introduced into the public realm.

6.4.2 Economic Challenges

Introducing a new vehicle and fuel into society requires substantial stakeholder commitment and support both in the short term and over the long term to make the economic case for both the fuel provider and the fleet / consumer operator.

Ensuring vehicle availability will determine the rate of network fueling station growth. With the cost of fuel cell vehicles in excess of $1 million dollars, the CA H2 Net effort must work with the automakers to identify the most likely vehicles to utilize hydrogen in the near-term, e.g., hydrogen and hydrogen blend ICE vehicles. Redesigned vehicles which incorporate cylinder storage and new technologies such as metal hydride storage are essential. To date, only one European manufacturer has designed a "ground-up" gaseous fuel vehicle providing fully integrated storage tanks resulting in sufficient vehicle range consistent with consumer expectations.

Strategically, these initial hydrogen ICE vehicles could be utilized in fleets with some models available as "cross-over" consumer commuter vehicles. This strategy could enable fleets to "anchor" the initial hydrogen station network.

Other identified obstacles are listed below:

Incremental Vehicle Cost: Funding mechanisms to offset the incremental vehicle costs may be necessary to change fleet and consumer behavior. State agencies and local government should serve as change agents procuring primarily gaseous fuel vehicles if auto and engine manufactures are to develop new vehicle platforms. The

Carl Moyer Program, the Mobile Source Air Pollution Reduction Program, and the California Energy Commission all have funded incremental costs for alternative fuel vehicles.

Station Funding: With high capital cost low volume stations and speculative volume, the initial station network will need to be funded through public-private partnership programs initiated through the CA H2 Net program. This funding will help to reduce the cost of hydrogen fuel. It is unclear whether operating costs can be fully recovered through the price of fuel and therefore may require additional support.

Fuel Subsidy: The cost of fuel will likely require a subsidy to be below the cost of gasoline or diesel. Fleets and consumers require a strong economic incentive to change behavior.

Transitional Funding: In addition to the economic issues identified above, fleet and auto repair operations may require support to retrofit facilities for gaseous fuel detection, alarms, etc. Additionally, mechanic and safety training will likely be required. The California community college system already has an extensive natural gas vehicle training program in place which has proven quite successful and which can assist in providing a trained work force in maintenance and safety.

6.4.3 Commercialization Barriers

Site Locations and Network Access: Identifying host locations to also provide public access facilities present a challenge. If state, municipal, and local agency fleets are initially leveraged to provide host locations, public access should be granted at these stations. Current liability issues often hinder public access at some similar fleet locations. Furthermore, universal public access (credit cards and video monitor fueling training) like that experienced at gasoline stations should be instituted to support early adopters.

Initial Network Limitations – Public Access: Targeting State, Transit, and other fleets can present a public access challenge. Agencies and fleets must be encouraged to offer “carve-out” public access. This “carve-out” retains fleet fueling behind the fence and public ingress-egress only to dispensers located outside the fence at the property edge.

Initial Network Limitations – Design Pressure: The lack of a consistent vehicle design pressure will limit development of a network. This critical design requirement impacts all aspects of introducing a new fuel from station and vehicle design to consumer outreach and acceptance (see Implementation Topic Team for more information on consistent codes and standards).

Permitting and Construction: Significant education is required with fire marshals and other City Agencies to facilitate gaseous fuel station development (see Implementation Topic Team for more information on permitting and construction).

Cultural Acceptance: Consumers will be the last to transition to another fuel besides gasoline or diesel. Non-conventional and limited fueling locations provide the first cultural barrier. Automakers offering limited production vehicles also present consumer concerns. High volume central fleets could allay these concerns and should be the initial target for introduction.

Public Policy: The State, Municipalities, and other Agencies should lead the transition to gaseous fuels within their own fleets and franchised fleets. Other gaseous fuel fleet requirements, such as those promulgated by the South Coast AQMD, could be used to gain awareness and understanding of high-pressure gaseous fuels in all segments of society. Executive Orders, Legislative and Policy directives and mandates may be considered to foster greater awareness and shift in societal habits.

Public Education: Awareness and safety campaigns for gaseous fuels should be widely implemented with sustained commitment. Broadening the awareness, understanding, and comfort with existing and future hydrogen and natural gas stations are critical to network expansion. With increased public acceptance the transition to a gaseous fuel future can become a reality (see Public Education Topic Team report for more detailed information).

Lack of recognized fuel providers to market and promote turnkey hydrogen stations: Without a recognized fuel provider (e.g., Shell, ChevronTexaco, Utilities, etc.) promoting and developing fueling infrastructure, the market will appear to be a random, vendor-based market development effort. Missing will be the business based focus of a fuel provider to install the best systems for overall durability, reliability, and cost. Economies of scale in building repetitive systems will be lost. Stations will be built one at a time. There will be no “collective” learning curve of a station provider learning from their mistakes and making appropriate corrections the next time out. Lack of legitimate fuel providers in the market at the early stage of network development means that mistakes will likely be made multiple times and getting to the right solutions and an integrated consumer friendly network will take much longer.

With enough planning, commitment, and hard work, most if not all of the aforementioned challenges and barriers to hydrogen fueling station development can be overcome. The key toward overcoming these barriers is enabling a legion of hydrogen and gaseous fuel champions, in both the public and private sectors, who will maintain a long-term commitment to implement the hydrogen fuel future.

6.5 Site Identification Criteria

Identifying good station locations depends on a wide variety of the items previously discussed. However, a key factor in identifying a site host partner is ensuring the top down leadership and organizational commitment to the project. The host’s willingness and commitment to procure vehicles or distributed generation along with providing sufficient space for a public access station is essential. Based upon the experience gained from past work with alternative fuels, this type of commitment from partners is a major predictor for the success of the project.

The following sections identify Target Site Host Partners along with Screening Questions for Host Partners. It is anticipated that these Host Partners will serve as the foundation for a station network beyond the 2010 timeframe until broad consumer acceptance is achieved.

6.5.1 Screening Questions for Host Partners

The following questions were developed to assist in determining host partner candidates:

1. Top down support and commitment to the project?
2. Internal champion for the project – ideally on-site?
3. Willing to purchase / lease available H_2 vehicles (or HCNG vehicles) now and as they become available?
4. Willingness and interest in procuring / leasing Distributed Generation?
5. Do the available H_2 vehicles meet the mission of the fleet?
6. Have adequate funding resources to contribute to vehicle purchase and maintenance?
7. Have adequate funding resources to contribute to the refueling facility construction and maintenance?
8. Have adequate funding resources to make the necessary maintenance facility upgrades, i.e., gaseous detection, ventilation, etc?
9. Commitment to gaseous fuel training of personnel?
10. Are there legal restraints (like leasing conditions, operating procedures, etc.) to the construction of an H_2 refueling facility and its use?

6.5.2 Target Site Host Partners

Based upon previous experience with alternative fuels and the likelihood for success, potential project partners and station locations include:

1. CalTrans locations
2. State locations
3. Federal fleet locations
4. City/Municipal sites
5. Transit properties
6. Existing natural gas sites
7. Existing retail gasoline sites
8. Existing Hydrogen facilities (pipelines, production facilities)
9. Auto dealerships
10. Air district locations
11. Airports
12. Refuse fleet facilities
13. Universities
14. Electric and natural gas investor owned utilities
15. Oil Refinery locations
16. Port Authority locations
17. Other Centralized Fleet locations

18. Municipal waste plants, landfills
19. Agricultural sites – commercial feedlots, agricultural waste sites

6.6 Site Selection Screening Criteria

In order to ensure the best projects and sites are chosen throughout the project timeline for the CA H2 Net, potential sites are to be screened based upon a series of criteria. Example criteria include: Station sites / project locations ability to serve as many hydrogen users as possible, their strategic location statewide, safety, economic factors, level of experience, and logistics. Along with the "Screening Questions for Host Partners" identified in the previous section, the following criterion should be used to evaluate Potential Sites and Projects:

A. Ability to Serve Maximum Number of Users
1. Proximity to several nearby fleets?
2. Public access station opportunity (direct access or facility "carve-out")
3. Proximity to stationary or other H2 users?

B. Strategic Location
1. Does the site support:
   (a). Regional Cluster (near term objective)
   (b). Inter-regional travel (now to 2010)
   (c). Inter-State travel (2010 and beyond)
2. Is the site private use only or will public access be provided?
3. Is it a high traffic volume location with sufficient ingress / egress?
4. Coordination with other nearby H_2 stations?
5. Does the site offer a "high" profile location?

C. Safety
1. Proximity to schools, hospitals or other sensitive locations?
2. Proximity to earthquake faults?

D. Economic Factors
1. Proximity to an existing or planned merchant H_2 source?
2. Anticipated utilization/throughput now and into the future?
   (a). H_2, HCNG, CNG light, medium-duty, and heavy-duty vehicle demand?
      (1) What is the load and demand profile for the station?
   (b). Demand for distributed generation co-generation?

E. Experience with Gaseous and Alternative Fuels
1. Current CNG operations?
2. Experience working with gaseous fueled fleets and vehicles?

F. Logistics
1. Adequate space for H_2 / gaseous fuel refueling equipment and infrastructure?
2. Suitability of the site for the various types of station (mobile fueling, delivered bottles, on-site production, etc.)?
3. What is the permanence of the proposed site?

4. Does the site already have adequate utilities (power, water, natural gas)? What utilities are required to develop the site?
5. Existing or ability to incorporate renewable energy equipment?
6. Proximity to renewable energy sources?
7. Restrictions on the use of the site (site lease, CCR, etc.)?
8. Support and experience of local city permitting agency and fire department? Have they permitted H2, CNG, or LNG facilities?
9. Potential for local incentives or special development zone funding?
10. Local neighborhood support?
11. Support of local utilities?

G. Additional Distributed Generation Considerations

1. On-site electric load that could utilize the power?
2. Thermal load that could be leveraged for cogeneration?
3. Potential for "over the fence" sales?

6.7 Implementation Plan

There are already a number of DOE and Agency funded hydrogen station projects underway. These initial projects are essential to provide showcase and technology demonstration opportunities. While these types of projects are critical to launching hydrogen as a vehicular fuel, the resulting stations are demonstrations and will not represent a real network with continuity, reliability, and access.

To move beyond demonstration projects, the CA H2 Net and the participating stakeholders have an opportunity to fulfill a critical role by continuing to review feasibility of technology for commercialization and accelerate standards for vehicle fueling such as standardized vehicle pressures so pubic investment is maximized and the private sector is encouraged to truly invest in network development. The rate of acceptance and development of gaseous fuel station networks will be guided by the rate which barriers are resolved and avenues to gain broad public acceptance are accelerated.

Provided here are recommended actions to support the development of the short, medium, and long-term hydrogen and gaseous fuel network in California.

A. Refine Site Host Partners and Locations:

An organization should be established with resources to review the identified target host locations and screen potential host partners to determine, rank, and refine opportunities. The effort involves:

1. Initially, solicit volunteers / host partners interested in providing station locations. Screen and rank partners.
2. Perform a more assertive site / host campaign from the identified targets should volunteer hosts be limited. Screen and rank partners.
3. Identify host locations that are critical to completing a regional network, whose existing resources can be leveraged and determine what is required to site a public access station. Screen and rank partners.

4. Map target locations determining regional clusters thereby establishing the baseline network.

5. Define expected implementation / site development timeline, clearly defining required station sizing.

B. Accelerating Station / Network Development

1. Support for hydrogen, HCNG, and CNG vehicle procurement, station development, facility modifications, and fuel subsidy using public-private partnerships will be essential. This support will determine the pace of station / network development.

   Funding is critical to facilitate the initial network development. Enable a funding mechanism to be focused on funding the shift to gaseous fuels for on-road vehicles: light-, medium-, and heavy-duty.

   Examples of funding mechanisms include a fuel discount for hydrogen, blended fuel (HCNG), and perhaps even natural gas vehicles as a bridging technology (funding mechanisms are addressed in more detail in the Economy Topic Team report). Hydrogen will initially be expensive compared to conventional fuels, therefore, some type of incentive will likely be necessary to prompt end-users (fleets and consumers) to shift from the status quo.

2. Federal, state, and local agencies should work with automakers to develop and deploy fuel cell, hydrogen and hydrogen blend ICE vehicles as early as possible. Government entities, transit agencies, environmental organizations, and other early adopters should consider multi-year purchase commitments to reduce the uncertainty of the automakers and fuel providers.

3. Encourage state and local agencies to modify existing utility distributed generation program criteria to further support hydrogen economics. This could be in the form of funding support for the utility Low Emission Vehicle programs as well as for hydrogen and hydrogen-blend station and fleet development. Lowering the utility transportation rates for gaseous fuels and distributed generation applications. This may also beneficially affect the utilization of hydrogen and gaseous fuels. (Currently, a filing is before the CPUC to reduce CNG tariff rates.)

4. Initiate gaseous fuel public awareness (print, television, radio) campaigns for hydrogen, gaseous fuels, and distributed generation (see Public Education Topic Team report).

5. Consider Executive Orders, state requirements, or other methods for phasing in vehicle purchases for gaseous, HCNG, and hydrogen fuels in the State fleets. For example, CalTrans and State fleets could be encouraged to purchase hydrogen, HCNG vehicles to help enable development of a wide range of vehicles enticing automakers or Small Volume Manufacturers to bring vehicles to market in this State.

Other measures could encourage private sector engineering, construction and development of stations on state controlled lands and establishing gaseous fuel displacement goals.

6. Support air districts, municipalities, and other agencies to resolve constraints enabling public / private partnerships providing public access.

7. California Air Resources Board (ARB) Programs

   The ARB could encourage gaseous fuel fleet utilization for transit, refuse, and airport fleets, which provide additional incentives for public access. This would rapidly spur the hydrogen station network development and dramatically increase public awareness, experience, and acceptance of high pressure gaseous fuels. As with the other alternative fuel introductions, without a strong statement by the ARB, most fleet operators will not change until economically required to do so, or mandated to do so, which does not foster a cooperative relationship with stakeholders. Other recommendations are discussed below:

   (a). Transit Rule

   The Transit Rule offers an opportunity to leverage those agencies which have already committed to the Fuel Cell / Hydrogen path by offering a bridging technology, i.e., HCNG or hydrogen HEVs, until fuel cell buses are commercially available. This action, particularly if public access is included, could quickly provide the foundation for the regional and statewide expansion of the hydrogen network.

   (b). Consider applying a similar rule to other sectors, e.g., Refuse Haulers, Postal Fleets, Regional Trucking (Port Authority, Distribution Trucking Centers, etc.), Taxis, and other high mileage gross-polluting fleets.

   (c). Investigate certification and verification processes for small volume manufacturers to provide safe and clean hydrogen, HCNG, and natural gas vehicles to enable the growth of the market.

8. Establish market based incentives for early adopters of dedicated gaseous fuel vehicles, such as:

   (a). HOV lane, toll bridge, toll roads access.
   (b). Free parking at State and city facilities, and Airports.
   (c). Reduced vehicle registration fees.
   (d). Provide corporations significant Rideshare offsets for employees commuting with dedicated gaseous fuel vehicles.
   (e). Establish an emission credit trading program.
   (f). Enable plant / facility expansions to be offset (a generous program would have to be established) by having a sizeable fleet

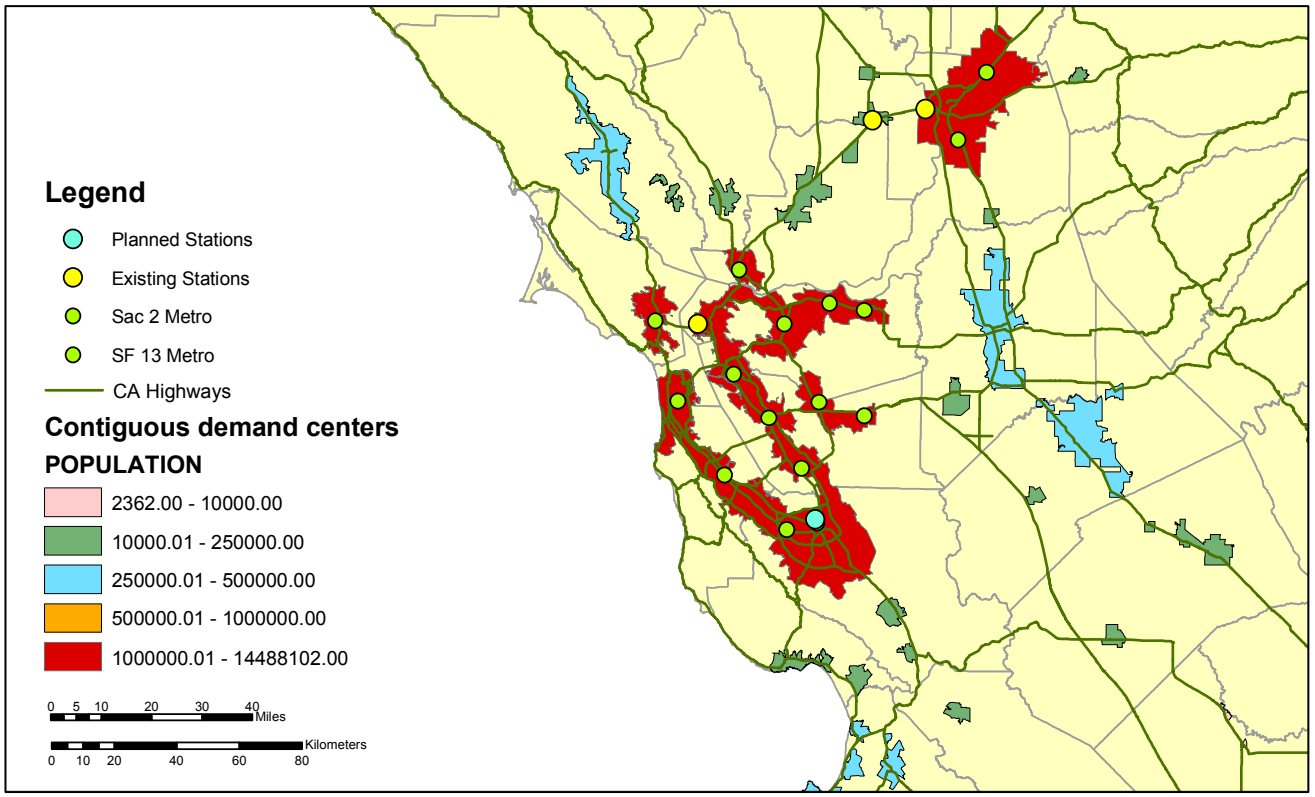
6.8 Illustrative Hydrogen Station Maps

Working with other teams, three network station scenarios were considered for illustrative purposes: Scenario A with 50 stations, Scenario B with 150 stations, and Scenario C with 250 stations. These are illustrated in the maps included here as Figure 6-1 (for Scenario A), Figure 6-2 (for Scenario B), and Figures 6-3 and 6-4 (for Scenario C). These three examples initially focus upon the four regional cluster areas of San Diego, greater Los Angeles (the SCAQMD area), San Francisco, and Sacramento. These areas represent what the subgroup was able to complete in the timeframe of this report. These maps should not be interpreted to mean that hydrogen stations will be clustered only in these areas.

For example, one of the areas not currently mapped, due to time constraints, is the San Joaquin Valley. The San Joaquin Valley is an attractive area to locate hydrogen stations due to its vast biomass resources and its severe pollution problem. Further, the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) has a long-standing policy of promoting alternative-fuel vehicles and has expressed an interest in participating in the CA H2 Net effort. Representatives from the SJVUAPCD served on various Topic Teams and the state will continue to work with them and other representatives from local governments to locate clusters of stations and vehicles in the Valley.

Important additional mapping features are as follows:

- Each scenario includes known and planned hydrogen stations identified with color coding.
- These station locations do not place a preference on the type of station and therefore equally represent all types of distributed generation and hydrogen station locations.
- Hydrogen stations are allocated based first upon population density and then by retail gasoline station densities.
- The 50-station example (Scenario A) allocates stations only in the highest density metropolitan areas.
- The 150-station example (Scenario B) expands the allocation into less dense surrounding metropolitan areas and utilizes a different color code for these expanded areas.
- The 250-station example (Scenario C) continues the population allocation of hydrogen stations but also includes bridging stations. These bridging stations are generally spaced 50 miles apart and are located in populated areas. The objective is to demonstrate the allocation of bridging stations enabling statewide transportation from Mexico to Oregon and to areas such as Lake Tahoe and Las Vegas, Nevada.



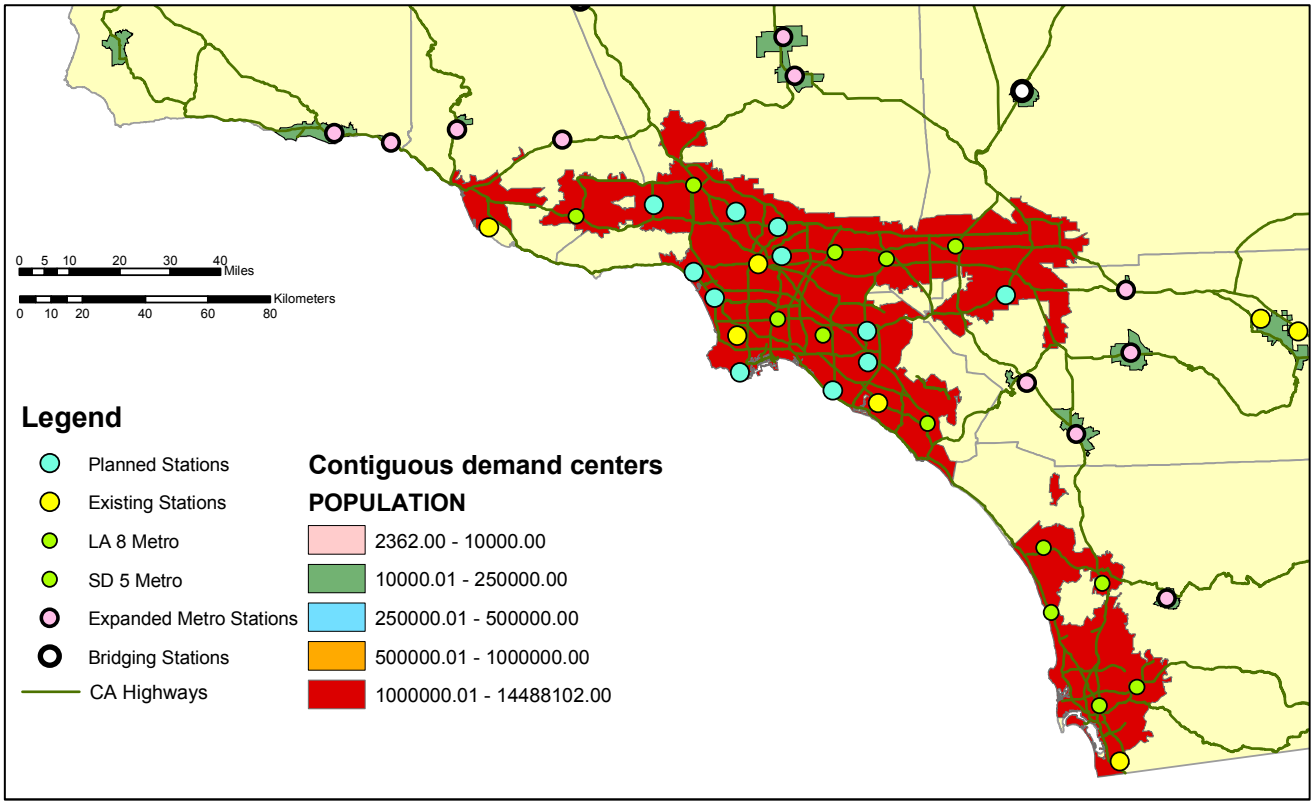
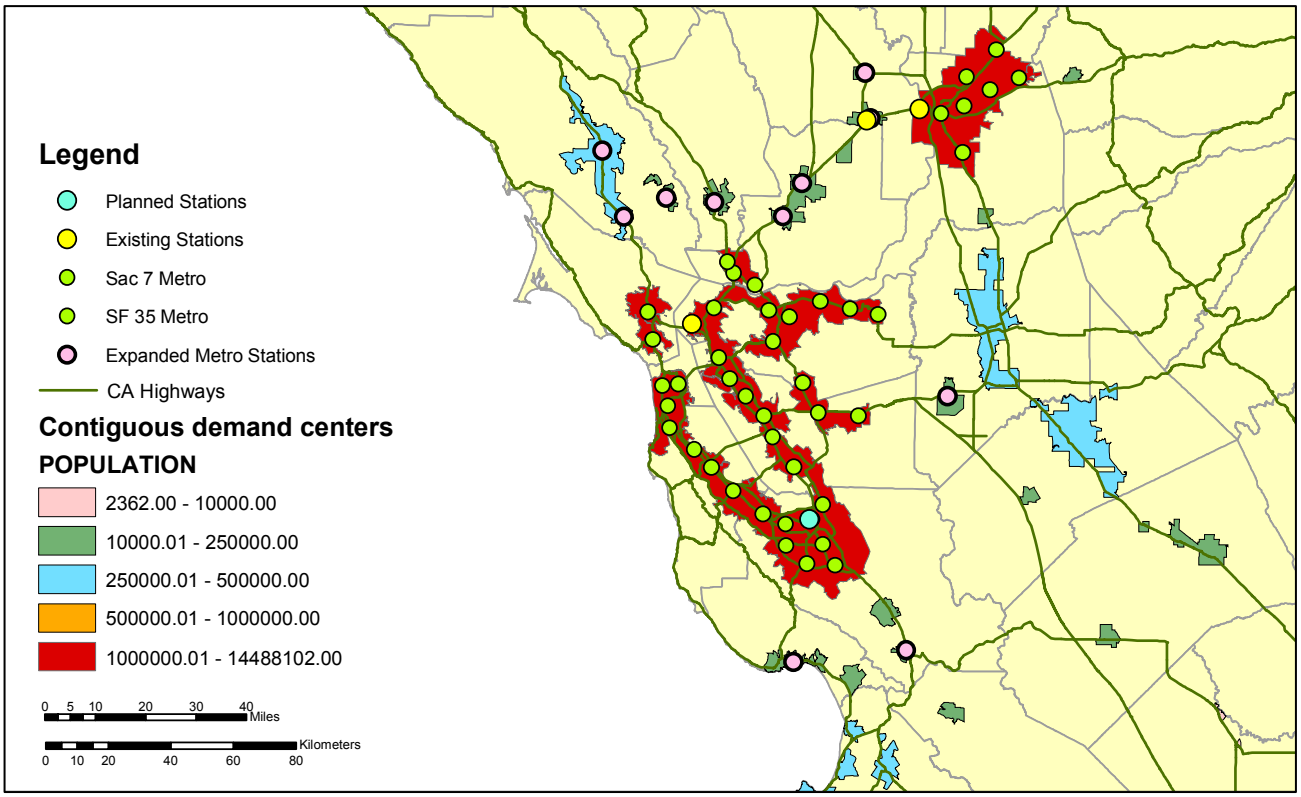


Figure 6-1. Scenario A, 50 Hydrogen Stations



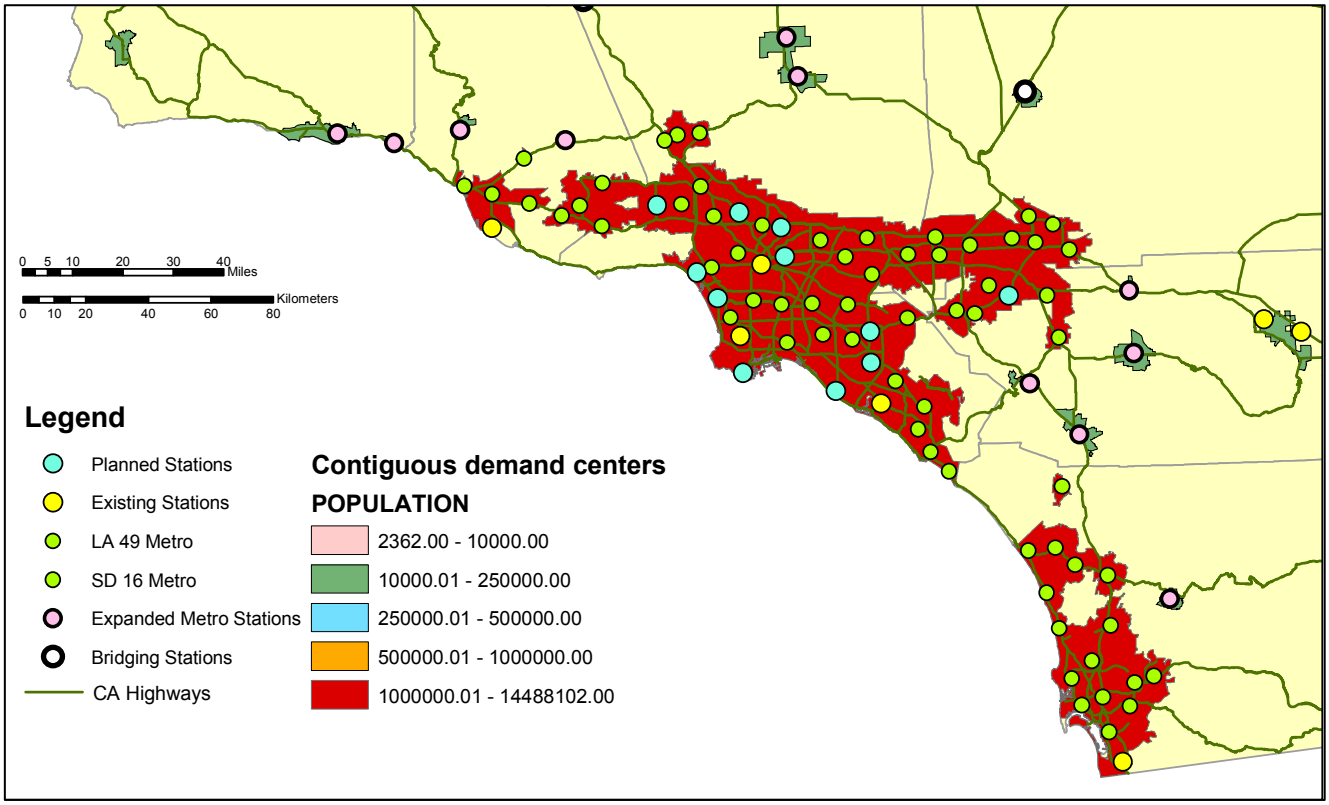
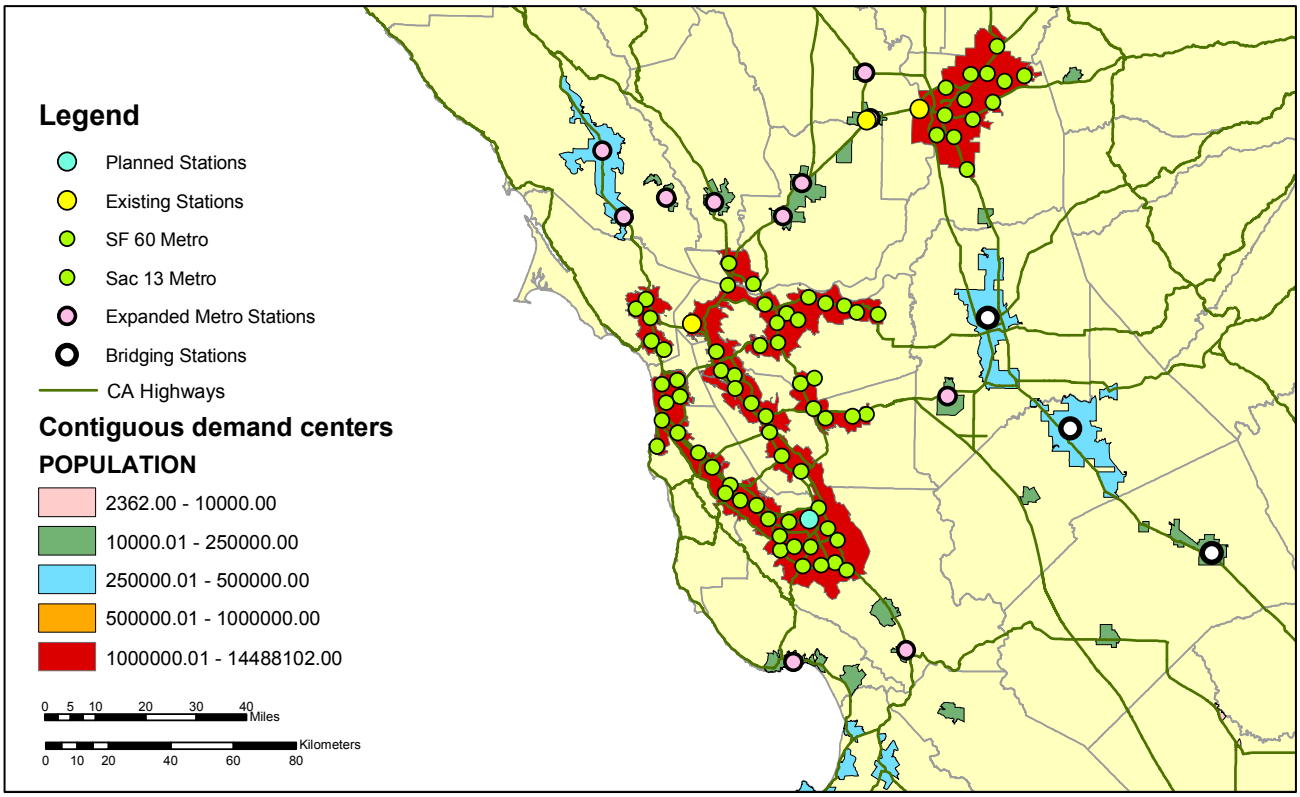


Figure 6-2. Scenario B (fleets) with 150 Hydrogen Stations



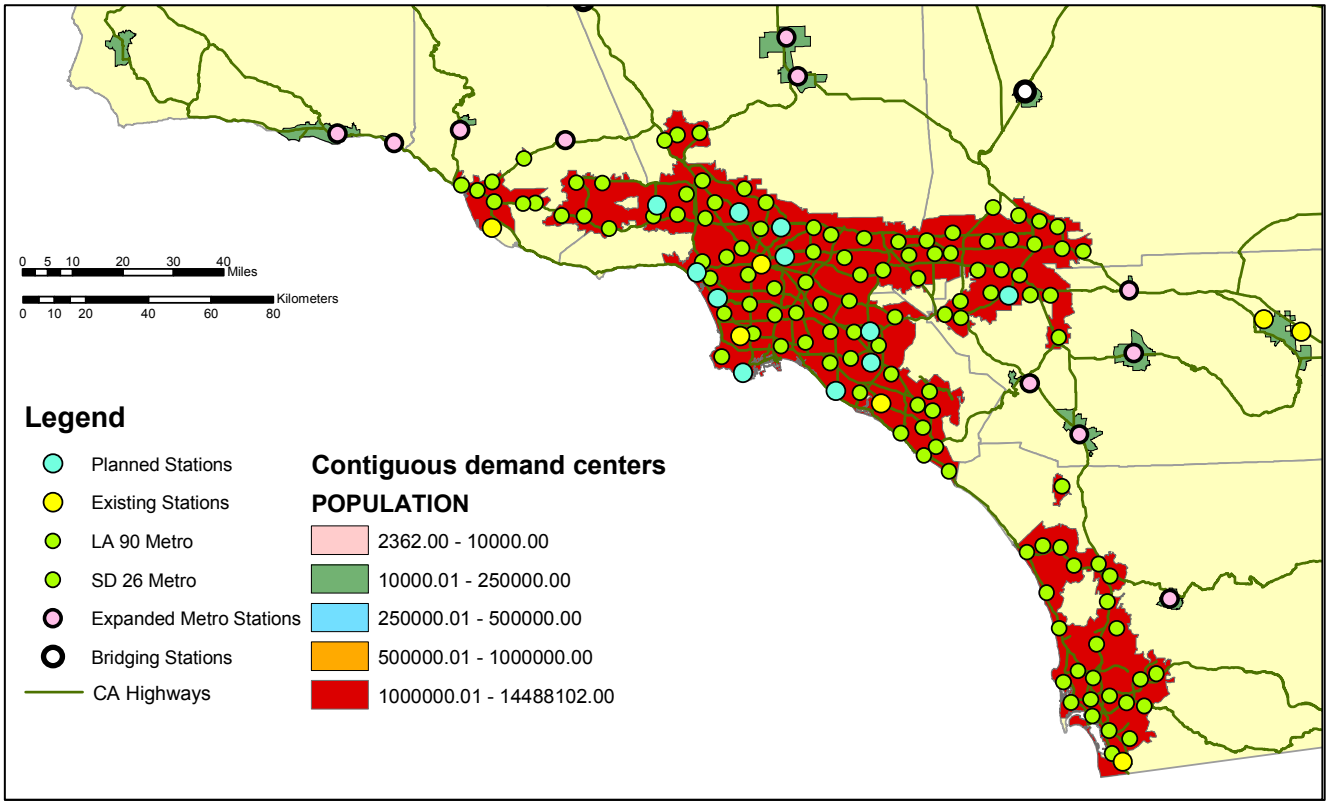


Figure 6-3. Scenario C, 250 Hydrogen Stations

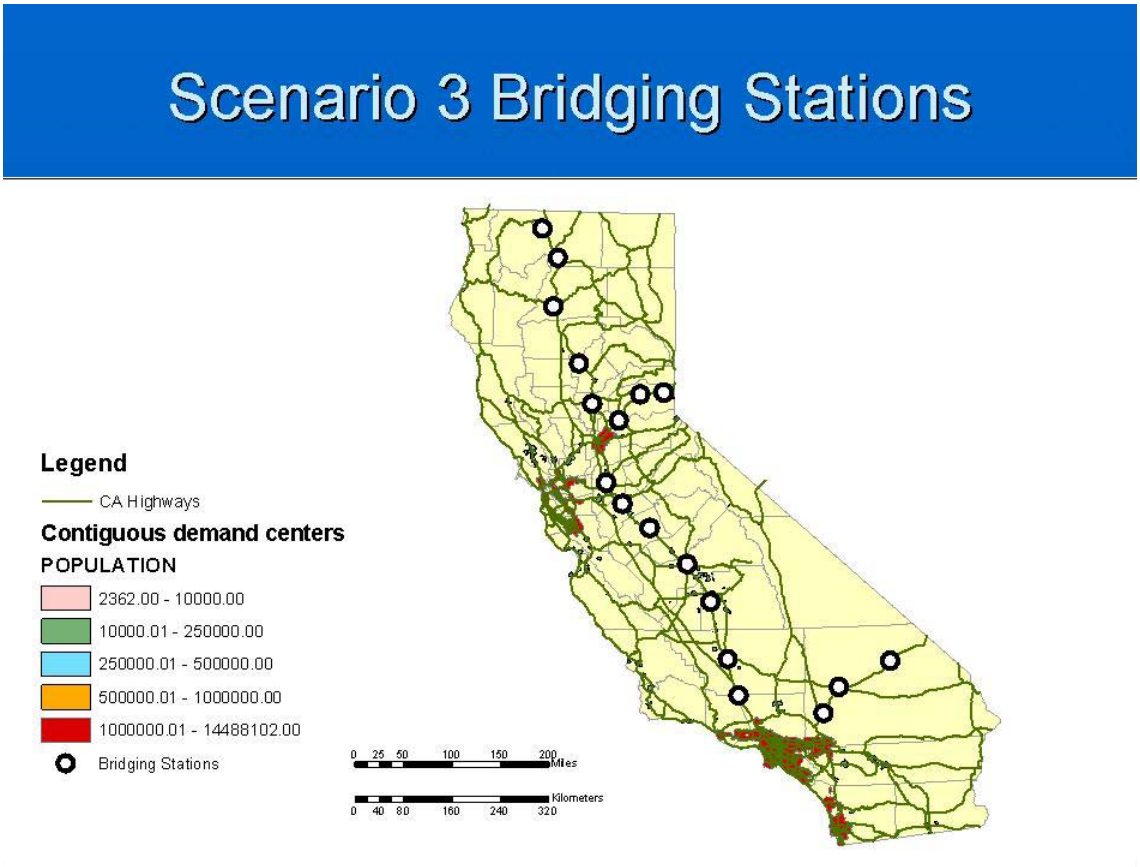


Figure 6-4. Statewide Map of Scenario C: 250 Hydrogen Stations

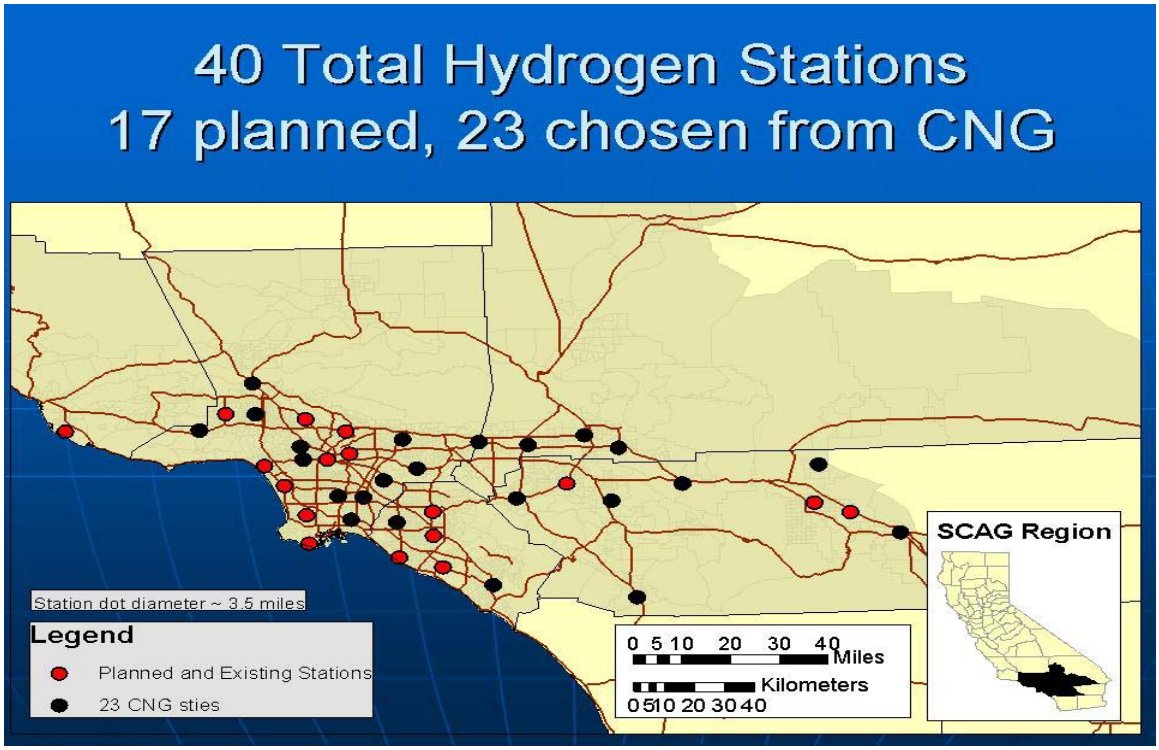
A more detailed analysis in the greater Los Angeles region (the SCAQMD territory) was also conducted. The resulting map, included as Figure 6-5, reveals an allocation of a variety of station scenarios in a fleet-based approach. This example utilizes existing and planned hydrogen stations, along with both existing natural gas stations and large population City locations as surrogates for a fleet-based rollout. These scenarios are of interest as they optimized for drive time utilizing population and gasoline station densities along with leveraging the fleet surrogates. Of greatest interest are the resulting drive time curves for the various station scenarios. As can be seen, it is a challenge to obtain the current average drive time to a gasoline station of approximately two minutes. Again, it is important to emphasize that other locations need to be mapped more thoroughly, such has been done for the SCAQMD.

6.9 Conclusions

Shifting entrenched societal dependency away from gasoline and diesel will take bold initiative and strong governmental leadership. Ultimately, for the private sector to invest its own capital into developing and managing a network of hydrogen stations, a strong economic case must be made. The economic case finds its foundation in realizing hydrogen throughput or demand. The identified initiatives and programs provide for both “market-push” and “market-pull” actions that are necessary for station developers,

automakers, fleet and ultimately consumers to transition to a new fuel. Overall, the timetable for implementing these actions will guide the development of the station network.

LA Region Station Drive Time Scenarios



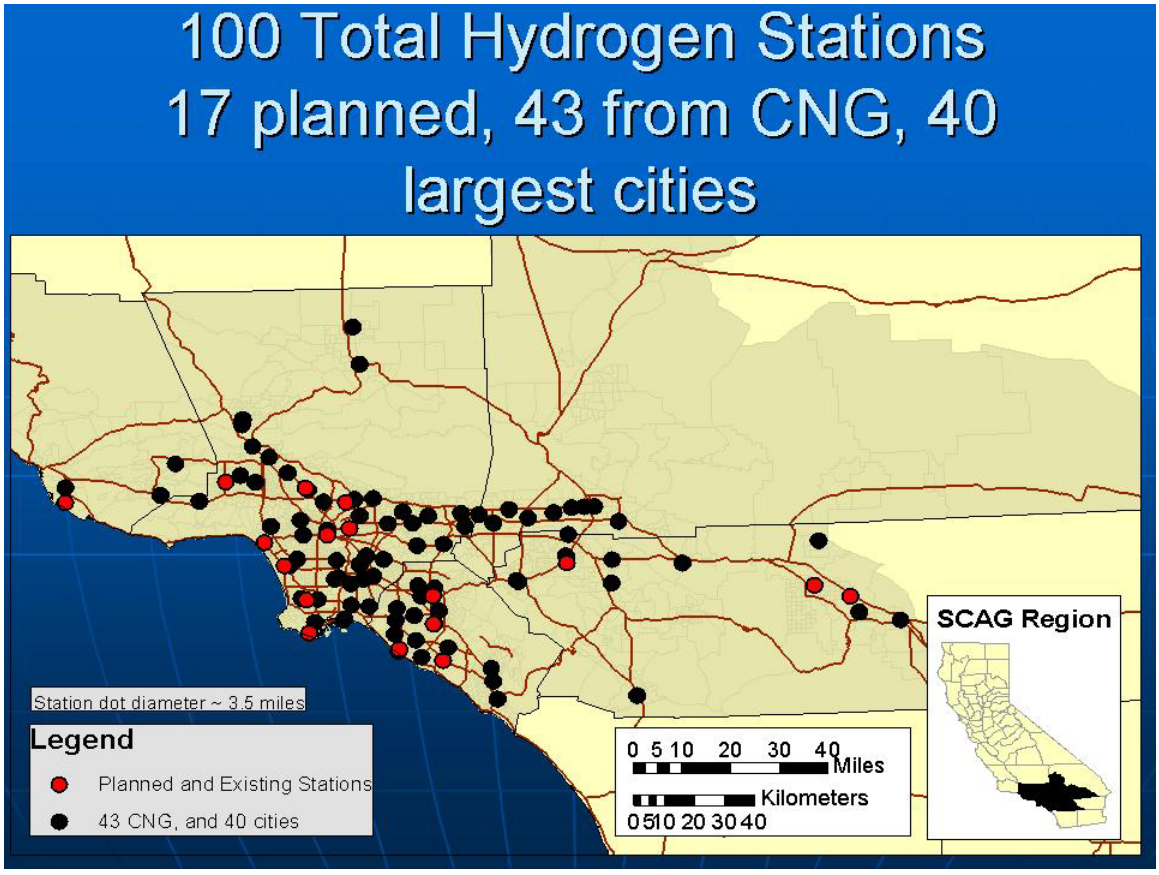
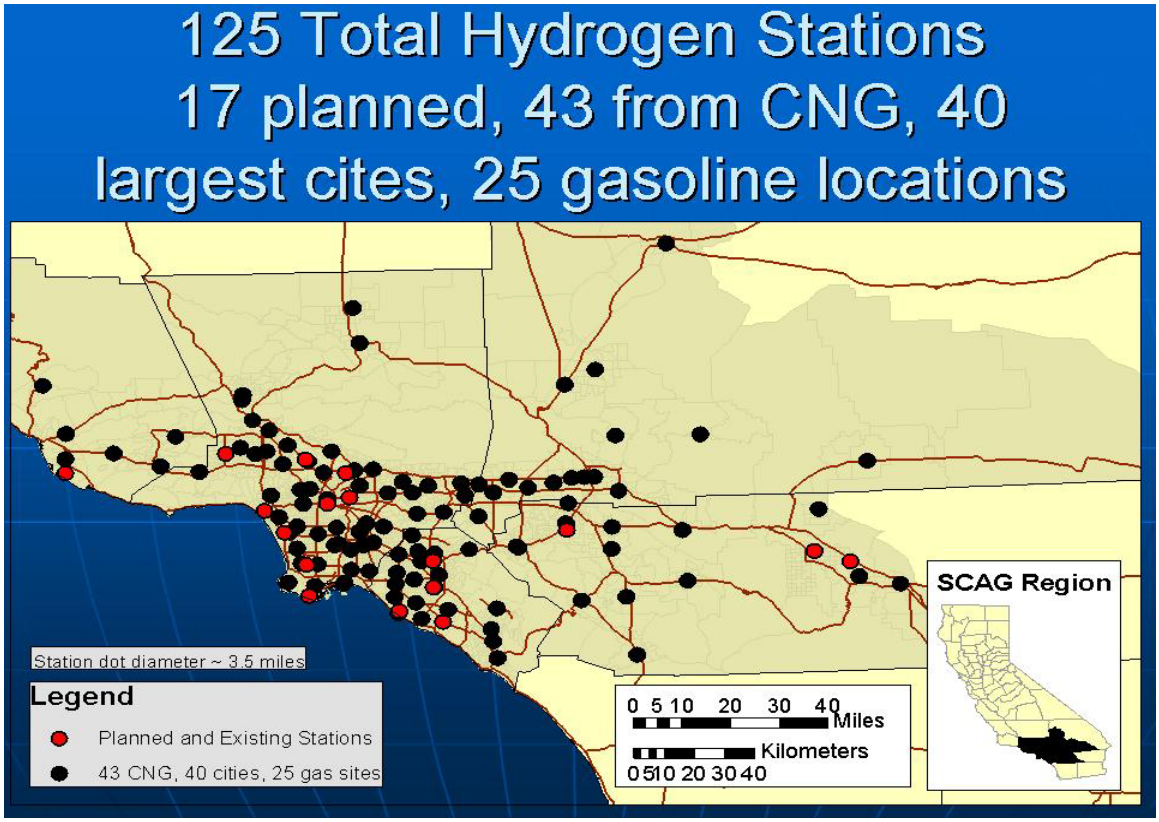


Figure 6-5. Los Angeles Region Drive Time Scenarios

LA Region Station Drive Time Scenarios



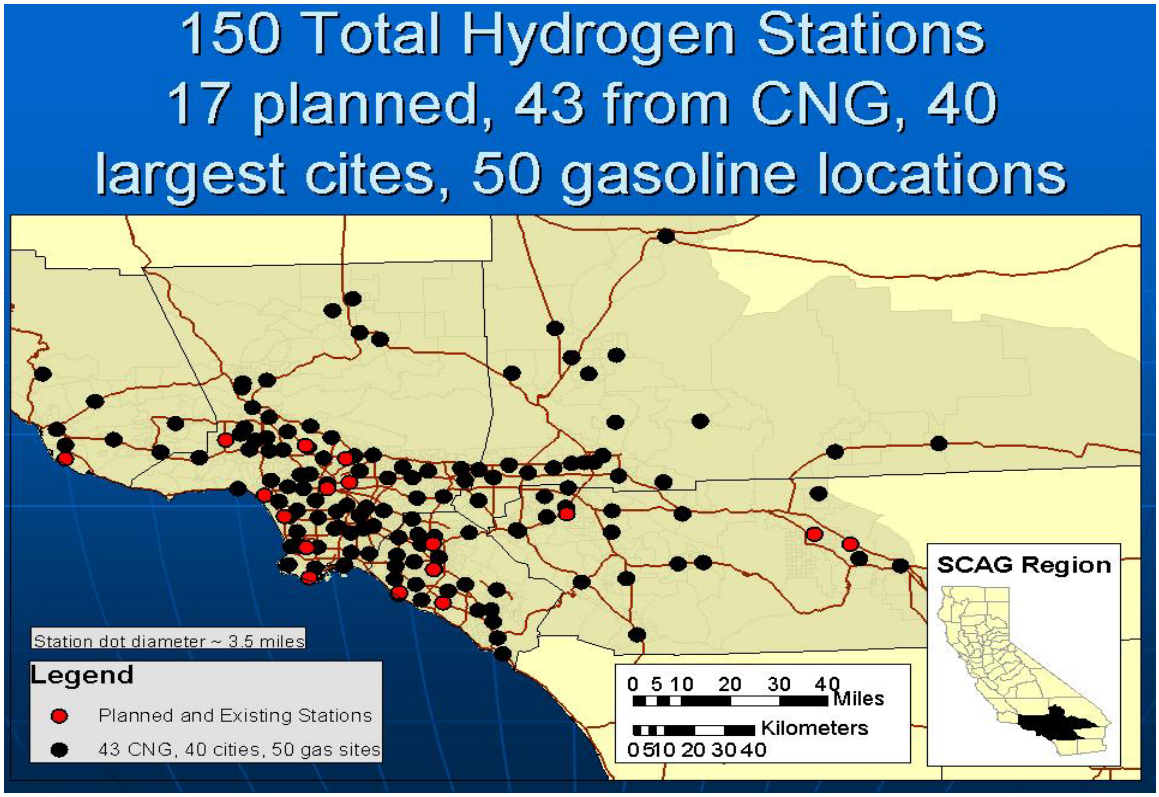
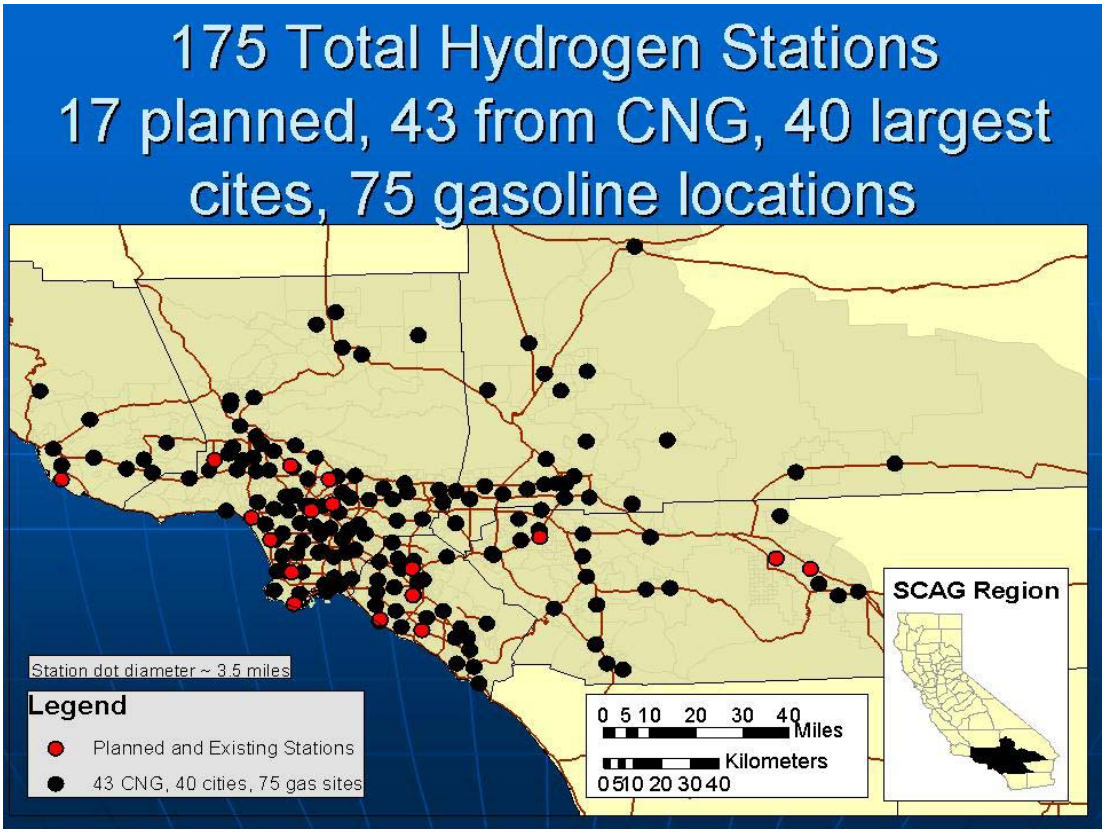


Figure 6.5. Los Angeles Region Drive Time Scenarios (continued)

LA Region Station Drive Time Scenarios



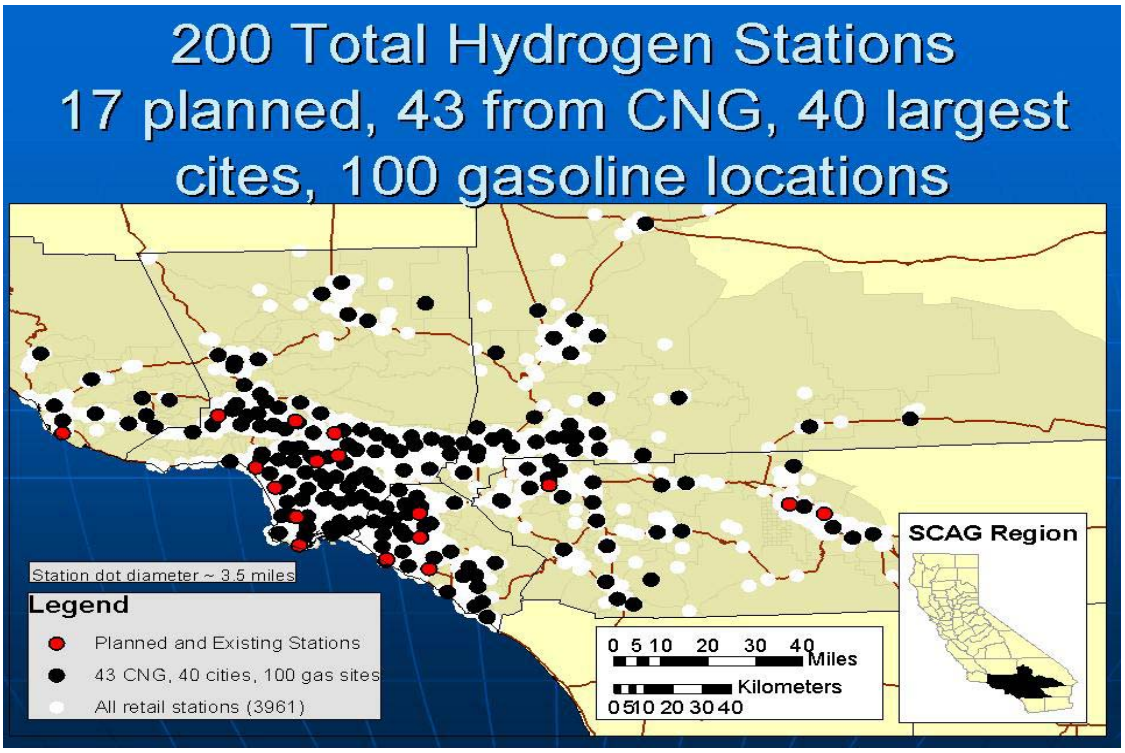


Figure 6-5. Los Angeles Region Drive Time Scenarios (concluded)

7. Recommendations

7.1 Overarching Recommendations

The Rollout Strategy Topic Team suggests three overarching recommendations with more specific subgroup recommendations presented following the overarching recommendations. The three umbrella recommendations are:

1. Formalize the Organization

Instead of the ad hoc group of volunteers assembled for the initial process, the organization of the CA H2 Net should be formalized into a structure empowered to:

- Coordinate and drive the effort by expanding established momentum
- Build on and strengthen constructive involvement of stakeholders
- Steer and adapt the program based on observations and learnings
- Coordinate and leverage external hydrogen initiatives (other U.S. states, Canada, Japan, EU)
- Investigate opportunities to integrate into the California Performance Review
- Establish a statewide Hydrogen Ombudsman
- Consider legislation, policies, and an executive order to foster development of the CA H2 Net

In order to implement many of the recommendations coming from this and other Topic Teams, a formal organizational structure with adequate resources will be required. For example, selecting the technologies for stations and applying the siting criterion will require dedicated staff resources. This staff should also be tasked with monitoring the implementation rollout to ensure the greenhouse gas and criteria pollutant goals are met.

This organization could also ensure the integration of the stations into a real network where communication of data is provided to all the stakeholders (OEMs, energy providers, agencies, and outside organizations/states/countries). This will allow the OEMs and energy providers to optimize placement of stations and vehicles. This would also provide high level visibility for rollout, as well as attract leveraging possibilities with other entities.

2. Mechanics of Implementation

In order to the enhance the success of the CA H2 Net, careful attention must be paid to the implementation of the early station deployments. Based in part on previous alternative fuel introductions and the limited hydrogen experience, the Rollout Topic Team offers these recommendations:

- Focus initial infrastructure in and between the highest expected vehicle/population centers, (i.e., Los Angeles, San Francisco, Sacramento, San Diego, and San Joaquin Valley)
- Maximize station utilization and experience gathering. Widely communicate these findings to foster positive public outreach and efficient implementation of codes and standards to the jurisdictional authority.
- Utilize, to the extent possible, past learnings with alternative fuel deployments.
- Sponsor improved models for station siting (and encourage industry-university involvement).
- Leverage existing hydrogen generation and fueling assets (e.g., CNG, gasoline, merchant hydrogen).
- Expand and adapt networks as vehicle population grows.

These actions will allow flexibility while providing an integrated effort versus pockets of disjointed demonstrations.

3. Leveraging

In order to fully capitalize on the current process, which involves the automobile manufacturers, energy providers, station builders, and government agencies, strategies should be implemented to leverage and springboard off the current momentum. Several of these recommendations are listed below:

- Establish Public-Private partnerships in each metropolitan region, with wide stakeholder participation for "coordinated differentiation" in each region. This could involve distinct government (local/state) and industry (auto, energy, supplier) consortiums in each region with limited participation. The strategy is to establish champions in each area which takes advantage of different station technologies, utilization via vehicles and stationary, and government participation such that distinct learnings are offered by the different regions. Although these regions would be different, the information should be communicated throughout the state in order to ensure coordinated efforts and reduced duplication.

- Identify industry and government agency incentives, financial and other, in order to reduce the risk and uncertainty of future liability to all stakeholders. For the early deployment of the CA H2 Net, government leadership is deemed necessary in order to reduce the risk the manufacturers, energy providers, and station operators will perceive. A coordinated, formalized organization will be able to analyze and adapt the best ideas from approaches used in Europe (i.e. "Lighthouse Projects"), Japan, and even recent DOE Infrastructure Demonstration projects.

- Work with other agencies, states, and countries to leverage resources and experiences. There are many different organizations and countries working on hydrogen and fuel cell projects. The CA H2 Net effort should work closely with these entities to leverage resources. For example, a joint request for proposals for vehicles could be released with the vehicles used simultaneously or shared in a series in various countries. Joint or similar policies or codes and standards could be

adopted to ease siting and fueling concerns, as well as spur increased vehicle production.

- Establish high school and community college curricula, as well as university research programs. The future of the energy transition will depend heavily on scientific perseverance (continued research) and valuing of externalities (public education), especially through outreach to the next generation of leaders. Establishing this foothold in high schools and college science curricula will be an important investment.

The following recommendations are those made by the subgroups of the Rollout Strategy Team, Production, Applications, Sites , and Commercialization. In many cases these recommendations overlap with each other and the overarching recommendations made above.

7.2 Production and Delivery Report Recommendations

1. Start now with a mix of production options that, to the greatest extent possible given technology and cost constraints, reflect the diversity of production options and the long-term goals of the CA H2 Net highway effort.

   For the purposes of developing the transitional CA H2 Net, the State should utilize a diverse spectrum of hydrogen production options that leverages those technologies for hydrogen production and delivery that are available today, or most likely to be available in the 2005-2010 timeframe. In addition it will be essential to include hydrogen production pathways that are likely to be needed in the future to ensure that California continues to move towards energy independence. In specific locales (e.g., Torrance), delivery through pipeline will play a role. Mobile refuelers can also be utilized. The DOE 2015 dispensed hydrogen cost goals ($2.85/kg for electrolysis and $1.50/kg for steam methane reforming (SMR)) are unlikely to be met by 2010. Therefore, we should not anticipate that hydrogen will be able to compete with gasoline in terms of cost on a per-gallon energy equivalent basis. In addition, the use of hydrogen as a fuel does not necessarily help solve pollution or greenhouse gas inventory problems in the near term. Indeed, electrolysis using electricity from the grid and SMR are not emission-free technologies unless CO_2 capture and sequestration are developed. Electrolysis from renewable resources (e.g., wind) is an emission-free process; however, this production pathway can only be utilized to a limited extent in the near-term.

2. Build consumer knowledge and gain acceptance of new technologies.

   Nearer-term consumer acceptance would need to be obtained based on demonstration of these technologies. One of the best ways to accomplish this is for consumers to personally experience the new technology via a ride on a transit bus, hands-on refueling, visit to Hydrogen Power Parks, or through other education and outreach activities planned under the various fleet demonstrations to be conducted in California through Industry/Government partnerships.

3. Leverage the synergy between the SCAQMD and DOE demonstrations.

   Significant activities are planned for the next five years in the State of California. Explicit mechanisms should be put in place, such as have begun under the early stages of the EO implementation planning, to ensure the State gains full advantage from the separate efforts and vice versa.

4. Develop hydrogen from renewable resources.

   In the time period beyond 2010 we anticipate that other technologies for hydrogen production will become technically viable, and could become economically viable. These “farther out” technologies include photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass and coal, high temperature thermochemical, and catalytic membranes. The DOE is sponsoring research aimed at advancing these technologies. The State may also wish to sponsor R&D in this area to explore any early opportunities to demonstrate and utilize hydrogen production from these pathways. In particular, centralized biomass gasification and wind-powered electrolysis can potentially have a larger impact in specific regions of California during the time period between now and 2010.

5. Promote the use of hydrogen in non-transportation applications.

   Hydrogen production technology development can be advanced through expanded societal use of hydrogen. This will enhance the case for a market for hydrogen leading to increased private sector investment. The use of hydrogen as an energy storage medium and in fuels cells for stationary power should be promoted.

6. Approach the transition in phases.

   The State of California can accelerate the development of hydrogen production and delivery technology options within our borders. Three phases of activities are envisioned: Phase I (now-2010), Phase II (2010-2015), and Phase III (beyond 2015). Some specific recommendations for these time periods are given below. These programs should be guided by an ongoing and balanced assessment of hydrogen vs. other alternatives to achieve California’s emissions, economic, and business climate goals.

7.3 Specific Recommendations for Phase I, II, and III

7.3.1 Phase I (now-2010): The Early Transition Period-Demonstrations, Technology Evaluation and Advancement, and Collaboration with Federal Programs

State funding should be provided for collaborative demonstration production projects involving private industry, universities, and California national laboratories. These demonstration projects should be done in collaboration/coordination with the existing and planned DOE infrastructure and fleet demonstration projects to best leverage resources. Obviously, emphasis should be given to co-locating distributed hydrogen

production demonstration technology at sites where FCV and hydrogen ICEV demonstrations/fleets are to be placed. Demonstration of reduced hydrogen costs and scalability for SMR and electrolysis should be priorities. In the early transition years, distributed production facilities with capacities of 50 to 250 kg hydrogen per day are the target. Emphasis should be give on the development of prototype designs for distributed production that can be commercialized in the following years.

1. In coordination with federal funding, utilize PIER funding for fundamental and applied R&D at California national laboratories and universities. Again, this work should be coordinated with the DOE program and used to fund promising technologies that might be under funded due to earmarking of the DOE budget or other constraints. The work should be focused on technologies that can exploit resources available in California. The major part of this funding should be directed towards technology development that could have an impact in the next 5 to 7 years. That is, additional funding should be provided for the development of those distributed production technologies that show current promise for ultimate wide scale deployment. This implies mass production and commercialization of units that can produce hydrogen at costs meeting or approaching DOE targets. Specific technologies include fuel reforming and electrolysis. In the area of advanced electrolysis, specific emphasis should concentrate on increasing system efficiency, lower cost materials and components, high pressure operation, and improved materials and system durability and reliability. Integration of electrolysis systems with wind and solar should also be addressed. Because they offer the promise of highest efficiency, the development of solid oxide electrolyzers (SOEs) should receive concentration

   In the area of fuels reforming (specifically SMR), emphasis should again be directed towards solving technical hurdles that will allow cost reductions and improve systems reliability and durability. Specifically, improvements in reactor materials and development of lower cost, higher activity catalysts are important. Demonstration of scalability (to smaller size systems in the 50 to 250 kg/day range) should also be given attention. Co-production of hydrogen and electricity, as a way of reducing overall hydrogen costs, should be considered and further developed for applications where this option is economically justified.

   Support should also be provided, albeit at less concentrated levels, for the development of the “farther out” production technologies. These technologies are not expected to play a significant role in hydrogen production until well after 2010. They include photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass (particularly the smaller-scale distributed option), high temperature thermochemical, and catalytic membranes. Fundamental research on photobiological hydrogen production would make use the outstanding bioengineering centers available in California universities and national labs. There are many groups within California investigating photoelectrochemical hydrogen research. The primary goal of work in these areas should be to attack the technical hurdles to higher efficiency and lower cost for hydrogen production using these processes.

2. Truck delivery to rural areas and smaller cities should be the principal method of providing hydrogen in the transitional period. Also in more remote rural areas, where natural gas pipelines are lacking, consideration should also be given to reforming of liquid fuels such as methanol and ethanol, as a truck distribution infrastructure for these energy carriers already exists.

3. Encouragement should be given to co-production of hydrogen (through electrolysis) at existing and planned wind and solar power sites. System integration and optimization issues need to be resolved and high efficiency under variable electrolyzer input conditions needs to be demonstrated.

4. While focusing on the development of Hydrogen Highways, the use of hydrogen and fuel cells should be promoted in stationary power production. The development of Hydrogen Power Parks should be encouraged with the public invited in as part of the public outreach/education campaign. These parks would not only be used for hydrogen refueling of vehicles but also for electricity generation in fuel cells. The Hydrogen Power Parks should function as demonstration sites for a variety of distributed hydrogen production technology options that show promise for economic and commercial viability.

5. The State should look for an early site to demonstrate the biomass production route for hydrogen, as well as ethanol and methanol from which hydrogen can be derived, given the strong synergy with resources in the State. Although the technology is further away, there may be a unique opportunity to begin the longer development curve.

6. The Hydrogen Highways Initiative should work with DOE in establishing appropriate safety, codes and standards for hydrogen production and use. Hydrogen purity requirements and refueling protocols are particular areas of interest.

7.3.2 Phase II (2010-2015): Implement Expanded Production Infrastructure — The Verge of Commercialization for FCVs and Expanded Stationary Power Uses

1. These years could see greatly expanded numbers of hydrogen ICEVs and FCVs (the latter still principally in fleet demonstrations) on California roads, advancing the case for mass production (commercialization) of FCVs. If these greatly increased numbers materialize, and consistent with hydrogen fuel demand, expanded distributed production infrastructure should accompany this increase. Depending on need, more refueling stations will need to be developed along highways and in rural areas utilizing the resources (feedstocks) most readily available in those areas, taking into consideration the economic factors involved. The use of fuel cells and hydrogen fuel in stationary power applications should also be expanded.

2. Demonstrations of wider scalability for SMR and electrolysis should be done. For these technologies, demonstrate that it is possible to achieve DOE hydrogen cost targets of $1.50/kg for SMR and $2.85/kg for electrolysis. If achievement of these cost targets can be demonstrated and there is sufficient hydrogen demand for high

station utilization, distributed station production capacities in the 250 to1,500 kg/day range should be demonstrated and deployed, particularly for SMR.

3. Advanced production technologies should continue to be developed through PIER program in conjunction with federal funding, and in partnership with the private sector. As technical hurdles are overcome and the case is made for commercialization, funding for SMR research should ramp down during this time period. Funding for advanced electrolysis research, particularly solid oxide electrolyzers (SOEs), should continue if there is a clear and economic commercialization pathway for this technology. There are more technical and economic hurdles for electrolysis using SOEs to overcome before the commercial case can be made for mass production. Early in this time period, the emphasis on SOEs should be directed towards the demonstration of prototypes with capacities in the 10 to 100 kg/day range. However, mass production of alkaline and PEM electrolyzer units in varying sizes can begin in this time period. Funding should be increased for the "farther out" production technologies of photobiological and photoelectrochemical, biofermentation, pyrolysis and gasification of biomass, high temperature thermochemical, and catalytic membranes. This funding should be contingent on successful research results indicating that it is possible to overcome scientific and engineering hurdles for these technologies so that the DOE 2015 hydrogen cost targets can be reached. During this time period, a down-selection process should be initiated to identify the most promising technologies in which to concentrate funding. This should be done in coordination with the DOE program, which will be investing significant resources into the development of all of these production methods.

4. Demonstrate commercial viability for co-production (electricity and hydrogen) Hydrogen Power Parks.

5. Optimize production and utilization of hydrogen as an energy carrier (energy storage medium) to facilitate the utilization of intermittent renewable sources of wind and solar. Compare economic viability with other means of integrating these intermittent resources, both with the grid and in stand-alone applications.

6. Poll public as to willingness to buy FCVs/H2 ICEVs and use hydrogen and use this information in establishing regional production options/station siting.

7.3.3 Phase III (beyond 2015): Full Implementation of the California Hydrogen Highways and the Extended Hydrogen Economy

1. In 2015 the automobile OEMs have stated that they will make decisions regarding mass production of FCVs. Hydrogen production will continue to rely heavily on fossil sources (e.g., SMR) although "carbon-free" hydrogen production options will continue to gain economic competitiveness. If the OEMs make a positive mass production decision and it is clear that the cars will be coming, the State should continue to encourage those advanced technologies that show promise for eventual commercialization in the years beyond 2015, concentrating funding in the down-selected technologies. Commercialization for these technologies should begin in the

2015-2030 timeframe. Production scenarios should rely on an optimized regional mix of technologies including renewable resources, and fossil-based that provide both environmental and economic benefits. Both centralized and distributed production should be utilized. Analytical models should be utilized to optimize the electricity grid/hydrogen production capacities for maximum efficiency, lowest emissions, and lowest cost to consumer. With appropriate technology and if extremely strong customer support materializes, mostly "carbon-free" hydrogen production system could be achieved before 2050.

2. Build hydrogen pipeline infrastructure within California for hydrogen delivery from centralized or sub-station production facilities. This should be complete by 2050. By then, the transition to a hydrogen economy in California can be accomplished.

7.4 Applications Report Recommendations

The review of hydrogen-fueled applications leads to observations, revealing several strategic opportunities and recommended actions:

1. Hydrogen fueled internal combustion engine vehicles, either as straight hydrogen ICEs, or hydrogen ICE-HEVs, can be available in significant numbers much sooner than fuel cell powered cars. Encourage the deployment of internal combustion engine vehicles using hydrogen fuel for early-on populating of the Hydrogen Highway. Fuel cell vehicles are expected to take their place in the vehicle fleet some years later, as and if they are ready.

2. Small companies are able to get products to market faster than large companies, but large companies can produce products in larger numbers. Therefore, encouraging small companies will get earlier deployments as well as foster competition, thereby demonstrating to the larger companies that there is consumer interest in these products, and causing them to make the necessary investments sooner. This can be accomplished by granting relief on expensive government and independent laboratory testing and certification processes. However, consumers generally prefer products from original equipment manufacturers, so market penetration will likely require large manufacturers.

3. Installing hydrogen refueling stations at existing CNG sites with new products that make dual use of major components will allow a quick deployment of stations at CNG stations, and keep costs to a minimum. This will result in a significant number of refueling stations early on to encourage vehicle purchases. It will minimize the cost of "stranded assets" during the early years of the deployment while throughputs are still low.

4. Allow manufacturers of refueling equipment to finance the government's purchase of that equipment. This will eliminate the need for government funds to be invested, and can be accomplished by agreeing to purchase a quantity of natural gas for the fleet from that vendor – purchases which may be made anyway.

5. Portable, off-road, and other hydrogen applications are proliferating, and encouraging these could potentially enable a product or products to catch on with the consuming public, dramatically expanding the hydrogen market.

6. Encourage technologies that increase efficiency, for example, plug-in hybrid vehicle technology. In this way the ultimate size of the prime mover, the most expensive component can be reduced, lowering the cost of the finished hydrogen powered product, and making the overall market transformation more achievable. Also, this reduces the amount of hydrogen needed, and consequent well to wheels emissions.

7. Blend hydrogen with natural gas at existing CNG refueling stations. It will further reduce vehicle emissions, while increasing the throughput of hydrogen in production, working to lower the cost. While existing NG vehicles may have to be modified to burn the blended mixture, availability of the blend will provide access to more vehicles.

8. Encourage the early development of stationary and off-road applications. These installations are already finding cost-effective niches in a surprisingly broad array of situations. Proliferation of these installations will:

    - Improve air quality
    - Increase throughput of hydrogen fuels and hydrogen carrier fuels
    - Provide a slipstream of hydrogen to supply a vehicle refueling station
    - Increase volume of fuel cells and other hydrogen applications manufacturing, reducing price
    - Help stabilize and reinforce the electricity distribution grid
    - Increase the reliability and quality of power to the facilities

In the process of communicating with companies making products that run on hydrogen fuel, the team heard further recommendations originating with those companies that the group felt worthy of listing. These are:

1. Encourage the Governor to challenge industry to build, and California residents and state government to buy, hydrogen fueled cars.

2. Provide consumer and manufacturer subsidies – predictable and declining

    - Tax credits
    - Tax deductions
    - Carl Moyer grants
    - Capital cost buydowns
    - Increase current spending on existing public goods programs
        - Focus strategically
    - Provide time and money to advance R&D

3. Enable markets for hydrogen products through government testing and certification and Codes & Standards development.

4. Develop projects at government facilities with a high public visibility profile

    - Stationary fuel cells at government sites
    - Purchase hydrogen vehicles for government use

5. Develop financing mechanism(s) to cover incremental cost to be competitive with non-hydrogen products

6. Provide a supportive regulatory environment for all hydrogen stationary applications by making available Power Purchase Agreements and Streamlined permit approval processes

7. Reach out to the public and special groups

    - Public officials informed about societal benefits of hydrogen and code implementation issues
    - Educated public comfortable w/ hydrogen in various applications
    - Hydrogen components inserted into K-12 education curricula
    - Celebrity endorsements

7. Provide special preferential treatment for hydrogen vehicles, such as access to high-occupancy vehicle lanes and preferential parking.

8. Make recommendations to the federal government:

    - Include hydrogen fueled vehicles in CAFE standard compliance calculations, using some multiple of the gasoline equivalent of the hydrogen mileage, as is currently done for alternative fueled vehicles such as ethanol vehicles.

7.5 Sites Report Recommendations

An organization should be established with resources to review the identified target host locations and screen potential host partners to determine, rank, and refine opportunities. The effort involves:

1. Initially, solicit volunteers / host partners interested in providing station locations. Screen and rank partners.
2. Perform a more assertive site / host campaign from the identified targets should volunteer hosts be limited. Screen and rank partners.
3. Identify host locations that are critical to completing a regional network and determine what is required to site a public access station. Screen and rank partners.
4. Map target locations determining regional clusters thereby establishing the baseline network.
5. Define expected implementation / site development timeline, clearly defining required station sizing.

In order to accelerate station and network development the Siting subgroup recommends the following:

1. Support for hydrogen, HCNG, and CNG vehicle procurement, station development, facility modifications, and fuel subsidy using public-private partnerships will be essential. This support will determine the pace of station / network development.

   Funding is critical to facilitate the initial network development. Enable a funding mechanism to be focused on funding the shift to gaseous fuels for on-road vehicles: light, medium-duty, and heavy-duty.

   Examples of funding mechanisms include a fuel discount for hydrogen, blended fuel (HCNG), and perhaps even natural gas vehicles as a bridging technology (funding mechanisms are addressed in more detail in the Economy Topic Team report). Hydrogen will initially be expensive compared to conventional fuels, so some type of incentive will likely be necessary to prompt end-users (fleets and consumers) to shift from the status quo.

2. Federal, State, and local Agencies should work with automakers to develop and deploy fuel cell, hydrogen and hydrogen blend ICE vehicles as early as possible. Government entities, transit agencies, environmental organizations, and other early adopters should consider multi-year purchase commitments to reduce the uncertainty to the automakers and fuel providers.

3. Encourage state and local agencies to modify existing utility distributed generation program criteria to further support hydrogen economics. This could be in the form of funding support for the utility Low Emission Vehicle programs as well as for hydrogen and hydrogen-blend station and fleet development. Lowering the utility transportation rates for gaseous fuels and distributed generation applications may also beneficially affect the utilization of hydrogen and gaseous fuels. (Currently, a filing is before the CPUC to reduce CNG tariff rates.)

4. Initiate gaseous fuel public awareness (print, television, radio) campaign for hydrogen, gaseous fuels, and distributed generation (see Public Education Topic Team report).

5. Consider Executive Orders, state requirements, or other methods for phasing in vehicle purchases for gaseous, HCNG, and hydrogen fuels in the state fleets. For example, Caltrans and State Fleets could be encouraged to purchase hydrogen, HCNG vehicles to help enable development of a wide range of vehicles enticing automakers or Small Volume Manufacturers to bring vehicles to the market.

   Other measures could encourage private sector engineering, construction and development of stations on State controlled lands and establishing gaseous fuel displacement goals.

6. Support Air Districts, Municipalities, and other Agencies to resolve constraints enabling public / private partnerships providing public access.

7. California Air Resources Board (ARB) Programs.

   The ARB could encourage gaseous fuel fleet use for Transit, Refuse, and Airports which provide additional incentive for public access. This would rapidly the hydrogen station network development and dramatically increase public awareness, experience, and acceptance of high pressure gaseous fuels. As with the other alternative fuel introductions, without a strong statement by the ARB, most fleet operators will not change until economically required to do so. Other recommendations are discussed below:

   - Transit Rule: The Transit Rule offers an opportunity to leverage those agencies which have already committed to the Fuel Cell / Hydrogen path by offering a bridging technology, i.e., HCNG or hydrogen HEVs, until fuel cell buses are commercially available. This action, particularly if public access is included, could quickly provide the foundation for the regional and statewide expansion of the hydrogen network

   - Consider applying a similar rule to other sectors, e.g. Refuse Trucks, Postal Fleets, Regional Trucking (Port Authority, Distribution Trucking Centers, etc.), Taxi's, and other high mileage gross-polluting fleets.

   - Investigate certification and verification processes for small volume manufacturers to safely and cleanly provide Hydrogen, HCNG, and natural gas vehicles to enable the growth of the market.

8. Establish market based incentives for early adopters of dedicated gaseous fuel vehicles, such as:

   - HOV lane, bridge toll, toll roads access

     – Free parking at State, city, and Airports
     – Reduced vehicle registration fees
     – Provide corporations significant Rideshare offsets for employees commuting with dedicated gaseous fuel vehicles
     – Establish emission credit trading program
     – Enable plant / facility expansions to be offset (a generous program would have to be established) by having a sizeable fleet converted to gaseous fuels

7.6 Commercialization Report Recommendations

1. State and local governments should meet one on one with the automobile manufacturers to discuss lessons learned from the previous alternative fuel vehicle programs and identify steps and programs needed for successfully introducing hydrogen vehicles.

2. Develop proposal for funding early years of hydrogen highway programs. The proposal should explore many options for generating funding and include methods to sell these funding proposals. Analyze options for incentives such as: state vehicle

sales tax exemptions, registration/licensing/livery fee exemptions, state income tax deductions equal to a substantial portion of the incremental vehicle cost, free parking, free fuel, HOV lane access, allowing H2 fueled taxis to move to the front of the queue, adding incremental taxi medallions for hydrogen fueled vehicles, etc.

3. Target early demonstrations to enhance successful deployment of early hydrogen vehicles. Based on previous alternative fuel vehicle programs, some market applications will have higher probability of successes over others. These successful demonstrations will build market momentum for broader commercialization.

4. Form or use existing partnerships to mobilize resources, expertise, and support to lay the groundwork for hydrogen commercialization such as developing standardized fueling stations or safety procedures, effective information campaigns, and channeling government funding. Assist in developing sustainable business case for developing technology and investing in hydrogen. Recruit local champions to serve as catalyst and task master.

5. Ensure public access to all hydrogen fueling station to the extent feasible especially if public funds are used.

6. Encourage government to be first customers of technology and fuel.

7. Develop outreach programs such as ride share programs offering attractive commuting alternatives: e.g., hydrogen shuttle bus or "ride share" bus "offices" with free broadband WiFi access, personal media stations (satellite TV/Radio), morning newspapers, etc.

8. Glossary

Glossary of Terms

From the Department of Energy (DOE):
http://www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm11r0.pdf

Coordinated Differentiation: A strategy to establish champions in each area which take advantage of different station technologies, utilization via vehicles and stationary, and government participation such that distinct learnings are offered by the different regions. Although these regions are different in geography, population and resources, the information should be communicated throughout the one point of contact, the state, in order to ensure coordinated efforts and reduced duplication.

Acronyms

AQMD	Air Quality Management District
ARB	California Air Resources board
ASME	American Society of Mechanical Engineers
ATR	auto-thermal reforming
BPV	Boiler Pressure Vessel
C&S	Code(s) and Standard(s)
CalEPA	California Environmental Protection Agency
CA H2 Net	California Hydrogen Highway Network
CaFCP	California Fuel Cell Partnership
CalOSHA	California Occupational Safety and Hazard Agency
CalTrans	California Department of Transporation
CARB	California Air Resources Board
CBSC	California Building Standards Commission
CCR	California Code of Regulations
CDO	Code Development Organization
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CH_2	Compressed Hydrogen Gas
CH_4	Methane
CMR	Catalytic Membrane Reactor
CNG	Compressed Natural Gas
CO	carbon monoxide
CO_2	carbon dioxide
dHSM	Dense Hydrogen Separation Membranes
DOE	United States Department of Energy
DOT	United States Department of Transportation
EER	energy economy ratio
EIR	Environmental Impact Report
EIS	Environmental Impact Statement

EO	Governor's Executive Order
EPA	U.S. Environmental Protection Agency
FCV	Fuel Cell Vehicle
FMEA	Failure Mode and Effect Analysis
GHG	greenhouse gas
H_2	hydrogen
HCNG	hydrogen and compressed natural gas
HDV	heavy-duty vehicles
HFCIT	Hydrogen Fuel Cell & Infrastructure Technologies (office of the DOE)
HICE	Hydrogen Internal Combustion Engine
HSM	hydrogen separation membrane
HTHSM	High Temperature Hydrogen Separation Membranes
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
KOH	aqueous potassium hydroxide
LH_2	Liquid hydrogen
LNG	Liquefied Natural Gas
LTHSM	Low Temperature Hydrogen Separation Membranes
N_2O	nitrous oxide
NO_x	oxides of nitrogen
OAL	Office of Administrative Law
OEM	original equipment manufacturer
Pd	Palladium
PEC	Photoelectrochemical hydrogen-production process
PEM	proton exchange membrane
pHSM	Porous Hydrogen Separation Membranes
PIER	Public Interest Environmental Research
POX	partial oxidation
PM	particulate matter
PPP	public-private partnership
PSA	pressure swing absorption
PUC	California Public Utilities Commission
PV	photovoltaic
QRA	Site Quantitative Risk Assessment
RA/M	Risk Assessment and Risk Management
ROG	hydrocarbon
ROP	Report on Proposals
RPS	California's Renewables Portfolio Standard
RSPA	U.S. Dept of Transportation Research and Special Programs Administration
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SDO	Standard Development Organization
SMR	steam methane reforming
SOE	Solid Oxide Electrolyzer
SPE	solid polymer electrolyte
UL	Underwriters Laboratories
VTA	Santa Clara Valley Transportation Agency
WTW	Well-to-wheel

References

[1] Internal data from Toyota Motor Sales, Inc.

[2] Fuel Cells 2000 is an activity of the Breakthrough Technologies Institute (BTI), a non-profit [501(c)(3)] educational organization formed to promote the development and early commercialization of fuel cells and related pollution-free, efficient energy generation, storage and utilization technologies and fuels. See the following sites (last visited 11/17/04) for information regarding fuel cell vehicles:

- http://www.fuelcells.org/info/charts/carchart.pdf
- http://www.fuelcells.org/info/charts.html#fcvs

Hydrogenics Power Module To Be Installed In Step-Van At Hickam AFB

- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=144158

[3] The following sites provide information on fuel cell buses (last visited 11/17/04)

- http://www.utcfuelcells.com/news/archive/2002-11-14.shtm
- http://www.vta.org/projects/ZEBs.html
- http://www.actransit.org/onthehorizon/fuelcell.wu
- http://www.htdc.org/hcatt/fcellbus.html
- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=114613
- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=96761

[4] The following sites provide information on a variety of specialty vehicles using fuel cells (last visited 11/17/04).

Specialty vehicles – survey information

- http://www.fuelcells.org/info/charts.html#special
- http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/Reports/DisplayReport/0,1620,823,00.html

Sailboats

- http://www.haveblue.com/pdf/brochure.10.30.02.pdf
- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=132581

Forklifts:

- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=120530
- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=109181

Utility Vehicles (Commercial Work Vehicle)

- http://www.deere.com/en_US/compinfo/envtsafety/innovation/ePower/
- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=97360

Heavy Duty Hauling Vehicles

Programs for heavy mine vehicles and locomotives in Montana and Canada

- http://www.fuelcellpropulsion.org/
- http://www.billingsgazette.com/index.php?id=1&display=rednews/2004/07/25/build/business/25-mine-truck.inc

Hydrogen commuter train development being pursued in NC

- http://charlotte.creativeloafing.com/2004-05-12/news_cover.html

Heavy Duty Tractors

Tractor trailer auxiliary power units developed by Argonne – 2010

- http://www.cmt.anl.gov/science-technology/fuelcells/tuffcell.shtml

Hydrogenics Power Module To Be Installed In Aircraft Tow Tractor

- http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=142904

Scooters

Hydrogen powered scooter in Germany

- http://neobike.net/bikes/scooters/aqwon.html

  Hydrogen-powered 2-and-3 wheelers in India: ECD-Ovonics development program utilizing Metal Hydride Storage, in both FCV and hydrogen-ICE configurations, with India's largest 3-wheel vehicle manufacturer, Bajaj Automotive Limited (BAL)- sponsored by USAID / DOE.

Marine Vehicles

San Francisco/Treasure Island Hydrogen Fuel Cell Passenger Ferry – 2010

- http://www.watertransit.org/publications/Final_Fuel_Cell_Ferryboat_Study_21_Aug_03.PDF

Commercial Work Vehicles
http://www.deere.com/en_US/compinfo/envtsafety/innovation/ePower/

[5] GM, LBST, BP, ExxonMobil, Shell, TotalFinaElf, (2002) GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study, L-B-Systemtechnik GmbH, Ottobrunn, Germany, September 27. (http://www.lbst.de/gm-wtw/)

[6] Lasher, S., et al., Arthur D. Little Inc. (Feb. 2002). Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles - Phase II Final Report. DOE report (http://www-db.research.anl.gov/db1/cartech/document/DDD/192.pdf)

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[13] http://www.plugpower.com/news/details.cfm?prid=177

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[15] This report can be found on the Propane Education & Research Council - PERC - website under their 2003 press releases, Propane-Powered Fuel Cell Technology Reaches New Heights, August 29, 2003; http://www.propanecouncil.org/newsroom/press_releaseDetail.cfv?id=216

[16] The following links (last visited 11/18/04) provide a wealth of information on product offerings, reports on installations, etc., for a wide variety of stationary applications:

Port Applications (seaport, airport, etc.)

LAX negotiating demo hydrogen fleet vehicles for airport operations– 2010

http://www.hydrogennow.org/HNews/PressReleases/LAX/LAX-1stCommFuelingStation.htm

Fuel cell auxiliary power units for container ships in port, Port of Long Beach, – 2010

http://www.aqmd.gov/news1/2002/portpr.htm

APUs

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=99225

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=132899

Back-up power

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=142064

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=90131

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=147922

Fuel Cell Product Reference Charts

http://www.fuelcells.org/info/charts.html#products

Chart of Installations of Fuel Cells to Date

http://www.fuelcells.org/info/maps.html#install

Sound Data for Fuel Cells

http://www.fuelcells.org/info/charts.html#noise

The Fuel Cell 2000 website contains an extensive cataloging of fuel cells in various applications

http://www.fuelcells.org/info/charts.html

[17] "Accelerating Hydrogen Refueling Infrastructure By Jointly Harnessing Resources With CNG Refueling Stations" C. Verdugo-Peralta. World Hydrogen Energy Conference, Montreal, Canada, 2002.

[18] http://www.fuelcells.org/info/H2Stations

[19] "Hydrogen Blended Natural Gas Operation of a Heavy Duty Lean Burn Spark Ignition Engine and its Impact on Emissions Reduction," S. R. Munshi, C. Nedelcu, J. Harris, (Westport Innovations Inc, Vancouver, BC, Canada), T. Edwards (SunLine Transit Agency, Thousand Palms, CA, USA), Sept. 2004.

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http://www.arb.ca.gov/msprog/moyer/gsecritz.pdf

Emerging Fuel Cell Developments at NASA for Aircraft Applications

http://www.fuelcellsohio.org/images/NASA_OFCC_brief.pdf

Fuel Cells Niche Market Applications & Design Studies

http://www.dti.gov.uk/energy/renewables/publications/pdfs/f0300205.pdf

Analysis of Utility Hydrogen Systems & Hydrogen Airport Ground Support Equipment

http://www.directedtechnologies.com/pubs/AnalysisOfUtilH2Sys-Airport.pdf

Final Report, Hybrid Electric Tow Tractor, MCAS MIRAMAR, Pollution Prevention Equipment Program

http://www.lakehurst.navy.mil/p2/servlet/DocServlet?wDID=407

Aviation Operational Measures for Fuel and Emissions Reduction Workshop

http://www.icao.int/icao/en/env/workshop/ottawa_2002/judith_bayer.pdf

Tug Aircraft Support Equipment, Stewart & Stevenson, Inc.

http://www.ssss.com/home/

Airport Sources of Air Emissions

http://www.techtransfer.berkeley.edu/events/air/2004/Kenney.pdf

Hydrogenics Power Module To Be Installed In Step-Van At Hickam AFB

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=144158

Hydrogenics Power Module To Be Installed In Aircraft Tow Tractor

http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=142904

Ballard Ecostar 80 to Power Airport Ground Equipment

http://www.eyeforfuelcells.com/ReportDisplay.asp?ReportID=1331

Ballard Power Systems Corporation, 80V AC Electric Drive System

http://www.ballard.com/resources/transportation/Ecostar_80V_AC_Electric_Drive.pdf

Commercial Airplanes, Fuel Cell APU Overview, Boeing

http://www.eyeforfuelcells.com/ReportDisplay.asp?ReportID=1331

[21] http://www.fuelcells.org/info/charts/MicroMarket.pdf
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[22] *The Hydrogen Economy — Opportunities, Costs, Barriers, and R&D Needs*, National Research Council and National Academy of Engineering, The National Academics Press, Washington, D.C., 2004.

[23] www.eere.energy.gov/hydrogenandfuelcells/

[24] "Grand Challenge for Basic and Applied Research in Hydrogen Storage," U.S. DOE Solicitation DE-PS36-03GO93013, July, 2003.

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[32] www.aqmd.gov/rules/html/r1192.html

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[35] Paul Leiby and Jonathan Rubin, "Understanding the Transition to New Fuels and Vehicles: Lessons Learned from Analysis and Experience of Alternative Fuel and Hybrid Vehicles," in *The Hydrogen Energy Transition*, ed. Daniel Sperling and James S. Cannon. Elsevier Academic Press, 2004

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