AB 1007 SCENARIOS

HYDROGEN FUEL CELL VEHICLES

06-IFP-1B
DOCKET
06-AFP-1
DATE MAY 3 1 2007
RECD. JUN 0 4 2007

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May 24, 2007

Hydrogen & FCV Implementation Storyline

I. Executive Summary

Note: All assumptions used to calculate estimates/results shown in Section I can be found at the end of this report in Section VII.

This Executive Summary outlines the estimates of hydrogen fuel cell vehicle penetration and the resulting effects on petroleum reduction and greenhouse gas (GHG) emissions. Hydrogen fuel cell vehicles (FCVs) are considered by many auto manufacturers to be the ultimate goal in alternative-fuel, light-duty vehicles (LDVs). At present there exist numerous technical barriers related to on-board hydrogen storage, automotive fuel cell technology, and infrastructure development that are hindering commercialization of hydrogen FCVs. In response to these barriers there has been significant investment by federal and state governments, and by industry in an effort to develop FCVs for deployment.

The penetration scenarios evaluated here are focused on the adoption of hydrogen fuel cell vehicles. While certain auto manufacturers – BMW and Ford in particular - support hydrogen use in internal combustion engines, the majority of major manufacturers are investing in hydrogen fuel cells because fuel cells offers emissions and efficiency advantages over hydrogen ICEs.

Hydrogen FCVs offer many benefits, most importantly that they are true zero-emission vehicles (ZEVs), offer significantly improved overall efficiency, and rely on an energy carrier that can be produced from a large variety of primary energy feedstocks. These combined benefits are driving the investment in and commitment to hydrogen FCVs.

Vehicle penetrations were estimated for two growth cases (business-as-usual & aggressive) in order to estimate the range of effects that hydrogen FCVs may have on the California transportation market. These vehicle penetration estimates are shown in Figure 1-1 and Figure 1-2.

Figure 1-1: Hydrogen FCV California Penetration Scenarios

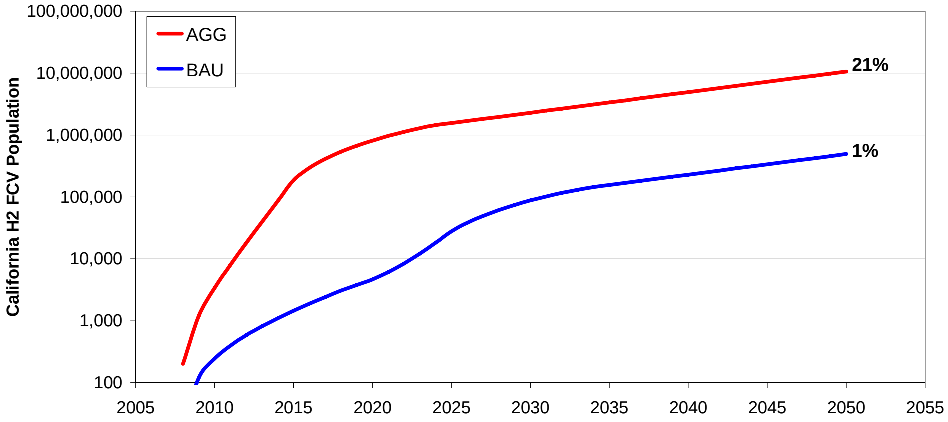
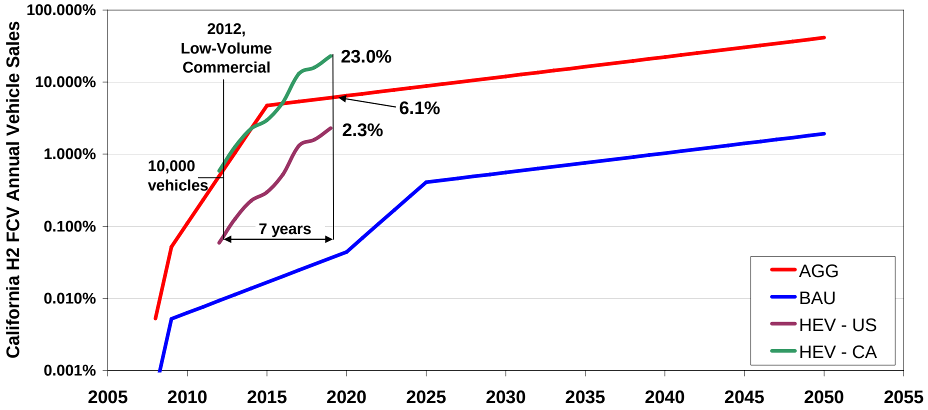


Figure 1-2: Hydrogen FCV California Sales Scenarios



The penetrations and sales volumes shown in Figure 1-1 and Figure 1-2 illustrate a business-as-usual scenario (BAU) and an aggressive scenario (AGG) in which the production schedule is accelerated and a majority of new FCVs are introduced into the California market. Figure 1-2 illustrates the fraction of new vehicle sales that must be achieved to yield the penetration displayed in Figure 1-1. In addition, Figure 1-2 shows sales penetrations illustrative of HEV sales during a period of similar technical development. The penetration curve "HEV – US" represents the national market segment for new HEVs from the point of low-volume commercialization (~10,000 units in 1999) to the present. The curve is shifted to coincide with the anticipated point of low-volume commercialization for FCVs in the aggressive case (2012). National HEV sales information[1] demonstrates that within seven years of low-volume deployment HEVs sales had reached 2.3% of new LDV sales in the U.S. If all of those vehicles were sold in California, HEVs would account for 23% of California LDV sales, as shown by the curve "HEV - CA". In order to achieve the aggressive scenario, production growth similar to HEV growth from 2000 to 2007 will provide a sufficient vehicle supply, but a disproportionate number of vehicles must be sold into the California market (to increase

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[1] DOE FreedomCAR and Vehicle Technologies Program, http://www1.eere.energy.gov/vehiclesandfuels/facts/2007_fcvt_fotw462.html

average sales from 2.3% to 6.1%). Without a disproportionate number of FCVs entering the California market, the national FCV sales would have to capitalize 6.1% of the new vehicle market. This would require production growth double that seen in the first seven years of HEV commercialization, which is unlikely given the success and effort put into growing the hybrid market in the U.S. Meeting the aggressive scenario will also require resolution of technical barriers, financial incentives to persuade OEMs to focus deployment in California, as well as the rapid development of a viable hydrogen infrastructure.

The development of commercially viable FCVs is paramount to the increased use of hydrogen in California. Hydrogen FCVs will utilize an electric drivetrain, similar to a series hybrid-electric vehicle (HEV), however instead of having an internal combustion engine (ICE) powering a generator or being assisted by an electric motor, the fuel cell will produce electricity directly. A small battery – similar to those used in a HEV – will allow for the capture of energy, through regenerative braking and smooth the transient demands on the fuel cell (a larger battery could also be used and allow plug-in operation).

The primary impediment to accelerating the deployment of hydrogen FCVs is the technical barriers presently hindering on-board hydrogen storage, automotive fuel cells, and infrastructure development.

Hydrogen Storage

Present conceptions of hydrogen storage, generally relying on compressed hydrogen, have difficulty achieving acceptable vehicle range (~300 miles) within the targets for volume, weight, and cost, as set by the Department of Energy (DOE). The California EPA/ARB *ZEV Review* indicates that continued development of compressed (700 bar) hydrogen storage will likely meet the 2010 targets for gravimetric and volumetric energy density, but fall short of 2015 expectations[2]. Additionally the *ZEV Review* does not predict significant cost reductions below the minimum estimated compressed storage tank cost of $1,650[3]. Further development of liquid and alternative storage techniques (metal and chemical hydrides, activated carbon structures) is likely required to achieve all the storage targets.

Automotive Fuel Cells

Automotive fuel cells have progressed significantly in recent years, but technical developments are still necessary to achieve the performance and cost goals necessary for a commercially viable product. The primary improvements required include simultaneously increasing the power density of the membrane-electrode assemblies (MEAs) to reduce the overall size of the fuel cell stack, reducing the catalyst loading and associated cost, increasing the operating life, and expanding the operational temperature range of the cell. Most of these developments will

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[2] California EPA/ARB, *ZEV Technology Review*, pg 150.

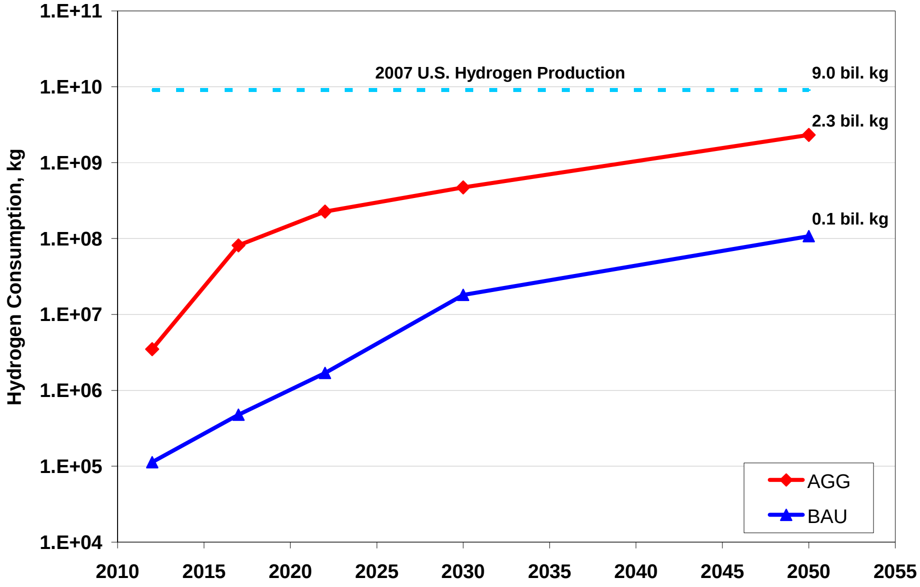
[3] Ibid.

provide both performance and cost benefits. The time and research and development (R&D) costs required to achieve these goals are presently unknown, but various developers are claiming that automotive fuel cell technology should be ready for commercialization anywhere between 2010 and 2020.

Hydrogen Production & Infrastructure

There is presently a substantial hydrogen production industry operated by industrial gas companies such as Air Products, Praxair, and Linde. Much of this hydrogen is used at refineries for hydrotreating gasoline, diesel fuels and other refined products in order to remove sulfur and other unwanted compounds. Hydrogen is also used extensively in the production of ammonia, methanol, rocket fuels and other commercial products. Total U.S. hydrogen production is approximately 9 million metric tons per year, more than 95% of which is produced by reforming natural gas[4]. Figure 1-3 illustrates the estimated California hydrogen consumption for both of the estimated scenarios, as well as the present U.S. production of hydrogen.

Figure 1-3: California FCV Hydrogen Consumption



As illustrated in Figure 1-3, the hydrogen production necessary to achieve significant market penetration in California would require a 25% increase of U.S. hydrogen production. Over the period of 2010-2050, this is a highly plausible increase in capacity.

While the magnitude of production seems feasible, the coordination of hydrogen vehicle deployment and fueling infrastructure construction is a classic "chicken-and-egg" problem. Vehicle deployment cannot occur without infrastructure and

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[4] DOE Office of Science, *Basic Research Needs for the Hydrogen Economy*, May 2003

> infrastructure development in the absence of hydrogen vehicles is not an economically favorable proposition. In response to this problem California has taken a proactive approach by supporting the development of the California Hydrogen Highway Network. As described in the *California Hydrogen Blueprint Plan* the Hydrogen Highway Network would, in three phases, construct 250 fueling stations in support of up to 20,000 hydrogen vehicles. The total cost, which includes \$18 million for vehicle incentives, is expected to be \$162 million, a portion of which will be covered by industry in a cost-share arrangement. A majority of these plants will employ on-site reformation of natural gas or electrolysis for hydrogen production. Further demand growth will necessitate the construction of larger fueling stations, central production sites, and pipeline distribution systems. Hydrogen is presently being distributed from major production facilities to refineries through large pipeline networks, particularly on the U.S. Gulf Coast. In addition to the expansion of hydrogen production and the distribution network, continued demand will likely lead to the development of home refueling systems that employ home-based natural gas reformation.

In order for these technical barriers to be overcome, funding for RD&D must continue from both the federal government and industry. The Hydrogen Fuel Initiative is presently funded through 2008 and will need to be extended and expanded if there is to be a hope of meeting aggressive growth targets. Increasing R&D effort is the key to accelerating the growth of FCVs.

Technical barriers are discussed in greater detail in Section IV.

With the continued development of vehicles employing electric drivetrains, a prime competitor to the FCV is the plug-in hybrid-electric vehicle (PHEV). The PHEV also promises high efficiency and significant GHG reductions through the combined use of large batteries, an electric drive and an ICE. In order to properly evaluate the performance of an FCV in the future market it is important to look at the potential gasoline displacement from FCVs in comparison to an equivalent population of PHEVs. Figure 1-4 and Figure 1-5 illustrate the potential for gasoline displacement compared to PHEV 20s (20-mile all-electric range) and PHEV 40s (40-mile all-electric range) for the business-as-usual and aggressive scenarios. These reductions assume the displacement of gasoline ICE vehicles having a Pavley-compliant fuel economy of 43.3[5] mpg.

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[5] Based on GHG emission standard of 205 g/mi and assumption of 8,875 gCO_2/gal

Figure 1-4: Gasoline Displacement, Business-as-Usual Scenario

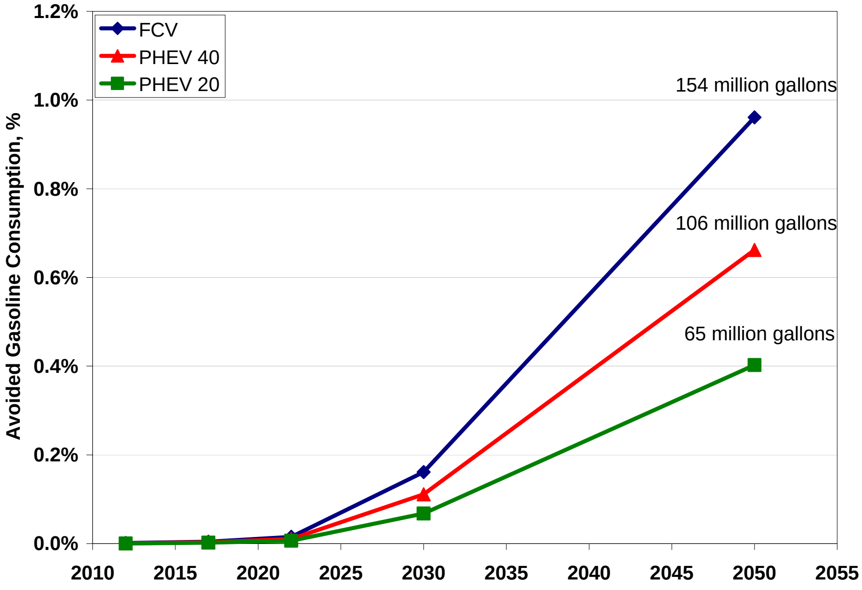
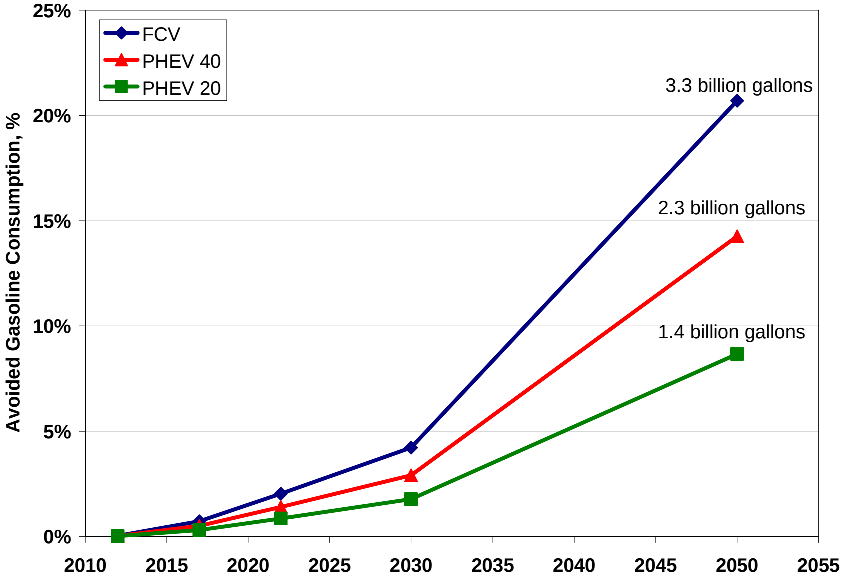


Figure 1-5: Gasoline Displacement, Aggressive Scenario



For reference, present California gasoline consumption for LDV use is approximately 16.0 billion gallons and expected consumption in 2025 and 2050 (assuming the adoption of Pavley GHG regulations) is 15.3 and 18.4 billion gallons.[6,7] The adoption of FCVs will yield an additional 6% reduction in gasoline usage by 2050 over the adoption of PHEV 40s, and 12% reduction over PHEV 20s.

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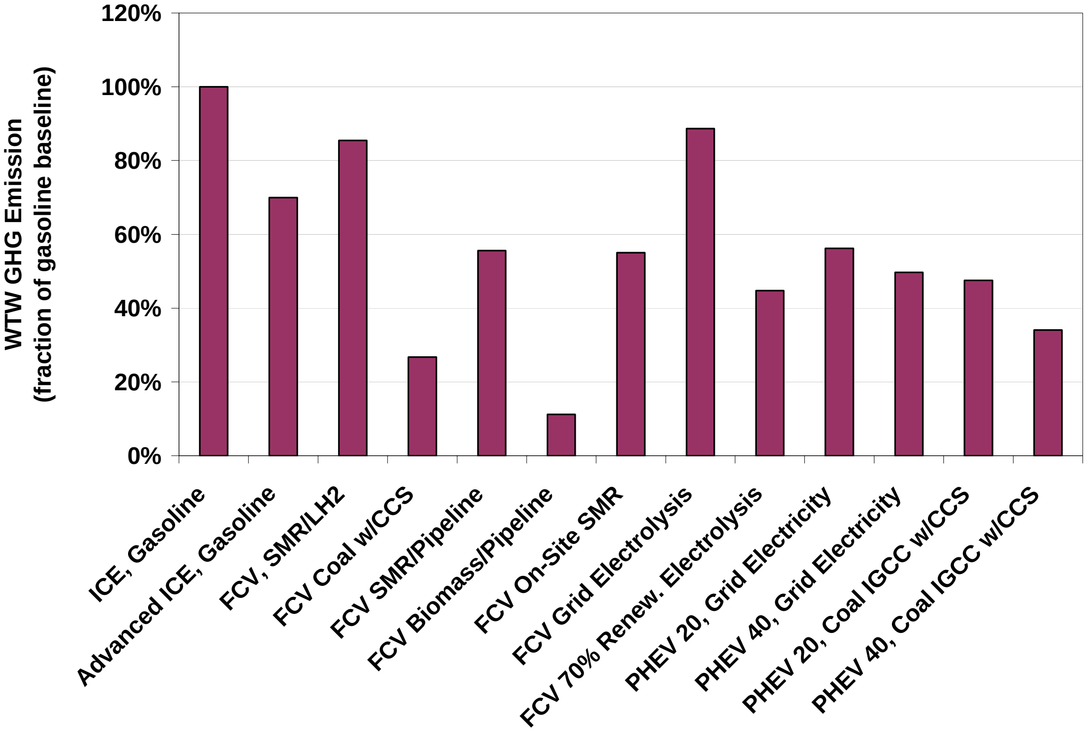
[6] CEC, 2005 IPER; *Forecasts of California Transportation Energy Demand*, April 2005.

[7] 2050 projection of 18.4 billion gallons assumes non-GHG regulated growth rate for years 2025-2050

In addition to reducing gasoline consumption, FCVs also reduce GHG emissions. Due to large number of production and delivery pathways, GHG effects are highly dependent on the upstream emissions associated with hydrogen production and delivery. Figure 1-6 shows the relative well-to-wheel GHG emissions from advanced gasoline vehicles, FCVs with hydrogen from a variety of production pathways, and PHEVs.

Figure 1-6: Relative GHG Emissions, WTW[8]



Note: Explanation of production pathways found in Appendix II

Figure 1-6 clearly illustrates the wide range of GHG benefits that can be achieved via the deployment of FCVs (terms defined in Appendix II). In reality, hydrogen production and delivery will be a mix of these available pathways, leading to a composite GHG reduction. Nevertheless, there are numerous potential pathways that will allow FCVs to achieve equal or superior GHG reductions to gasoline ICE vehicles and comparable reductions to PHEVs.

The variety of hydrogen feedstocks has numerous benefits for both automakers and consumers. Creating and using vehicles that can utilize a variety of energy sources liberates both parties from the volatility of the petroleum market. It is clear that petroleum is not an unending resource, making it wise for auto manufacturers to develop the technologies that will allow them to survive, or even thrive, in a post-petroleum world. Many OEMs are investing hundreds of millions of dollars in FCV development which reveals their belief that FCVs are vitally important to their long-term viability.

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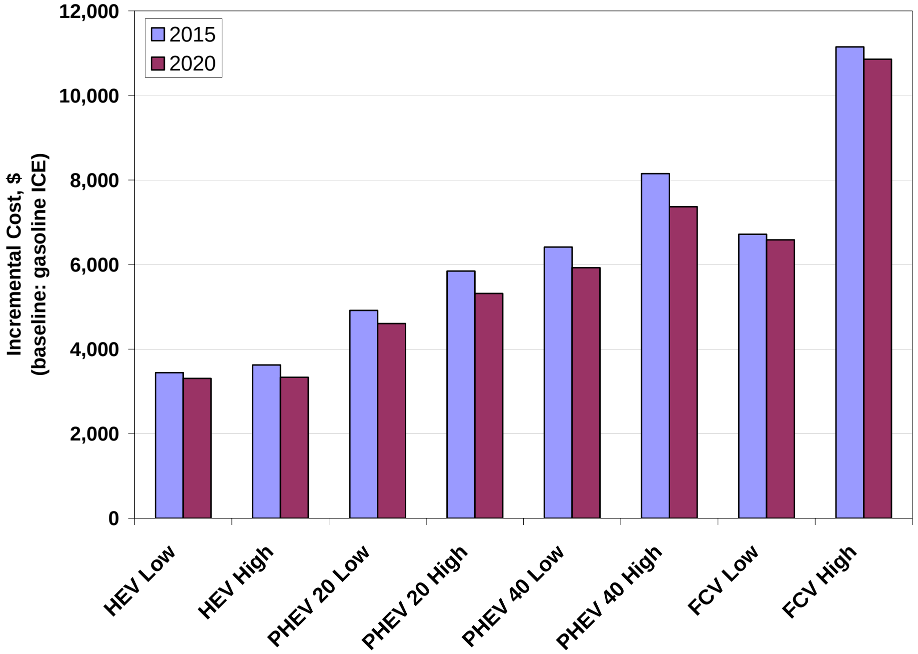
[8] AB1007, WTT Report, TIAX 2007

While the time horizon of the consumer is shorter, it may nevertheless be beneficial for a number of reasons, one being financial, to reduce dependency on petroleum fuels and the volatility of their price and availability.

In addition to the benefits provided by hydrogen FCVs it is necessary to analyze the cost required for significant deployment. Two major costs have been estimated here: incremental vehicle cost and infrastructure cost. The incremental vehicle cost has been estimated by adding the fuel cell and hydrogen storage cost to an HEV platform (and subtracting costs for the ICE and gasoline storage). Due to the inherent difficulty in predicting future cost, ranges were used to bracket the potential incremental costs with a high and low case. The most reliable cost numbers were provided for large production volumes (>100,000 units/year). Incremental costs for FCVs and PHEVs are shown in Figure 1-7.

Figure 1-7: Range of Incremental Vehicle Costs[9]



As illustrated by Figure 1-7, even with significant improvements in hydrogen storage and automotive fuel cells, there will be an incremental cost associated with the purchase of hydrogen vehicles. This analysis has estimated high-volume (>100,000 units annually) incremental costs to be between \$6,500 and \$11,000 per vehicle depending on whether certain cost targets are achieved. For low volume production, incremental costs were estimated to be between \$15,000 and \$30,000/vehicle, steadily decreasing to the high-volume cost. In order to create market demand, these incremental costs must be offset by a combination of incentives and consumer preference. Characteristics of hydrogen FCVs that may incent customers include: reduction of carbon emissions, protection against volatile oil prices, reduced vehicle noise, new and unique styling, access to HOV lanes

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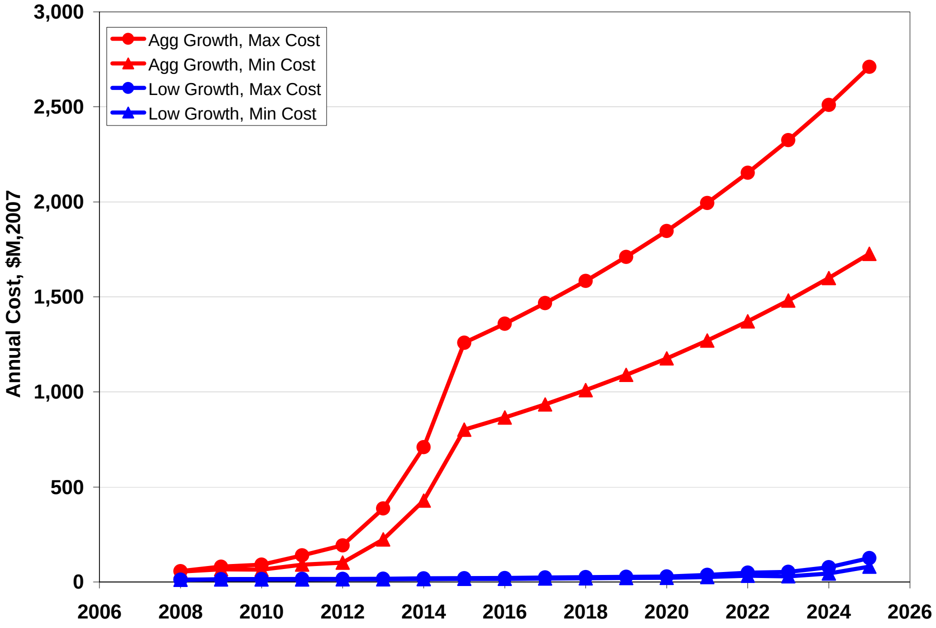
[9] California EPA/ARB, *ZEV Technology Review*, pg. 149 and TIAX Analysis

(enabled by certification as a zero-emissions vehicle), and the potential for home refueling, cogeneration, and use as a backup power supply.

Initial infrastructure costs in the near term (<20,000 vehicle population) were estimated based on cost projections for the California Hydrogen Highway, a 3-phase project to construct 250 hydrogen fueling locations serving 20,000 vehicles[10]. In the following years, larger hydrogen stations (1,500 kg/day & 2,250 vehicles served) are added to keep pace with vehicle growth. The infrastructure and vehicle costs are combined and shown in Figure 1-8, as actual dollar costs, and in Figure 1-9, as discounted costs assuming a 10% discount rate.

Figure 1-8: Annual Cost of Hydrogen FCV Deployment



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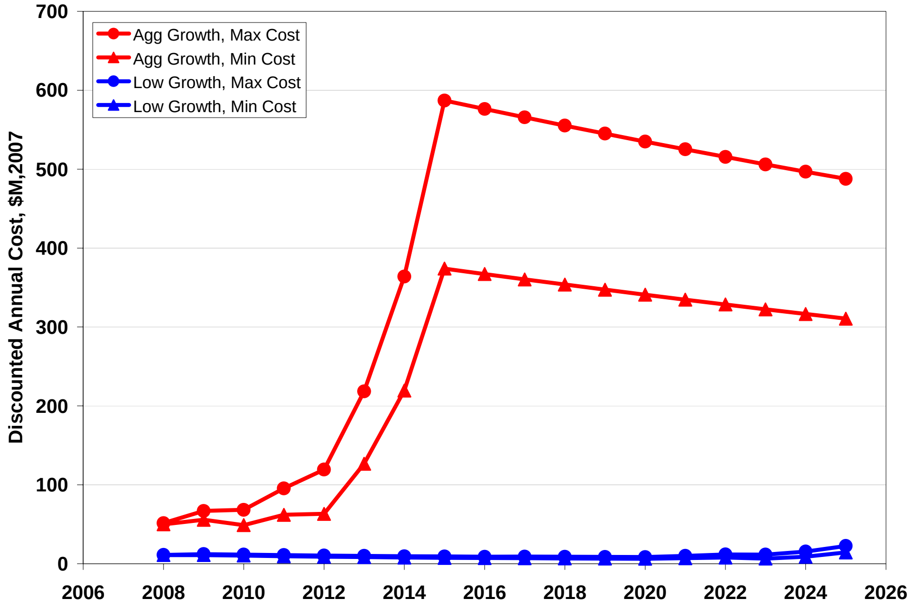
[10] California EPA, *California Hydrogen Blueprint Plan*, 2005.

Figure 1-9: Annual Discounted Cost of Hydrogen FCV Deployment



The cost of delivered hydrogen will also play a role in the overall economics of FCV adoption, but has not been included in this analysis. Estimates for large scale hydrogen systems (10% of regional fuel use) indicate that delivered hydrogen will cost between $2-4/kg[11] which is similar, but generally higher – on an energy basis - to future projections (to 2025) of gasoline price between $1.90 and $2.50/gal.[12] The efficiency benefits of an FCV will improve hydrogen's market competitiveness on a $/mile basis. The hydrogen cost projections do not pertain to near-term and/or small scale systems. Estimating the price of hydrogen in the transition is highly speculative; therefore it is not attempted in this analysis. It is assumed that hydrogen costs will be comparable to gasoline costs and are not a primary differentiator between gasoline ICE vehicles and hydrogen FCVs.

The costs shown do not include government and industrial financing of RD&D. Present annual funding is estimated to be between $600 million and $1 billion annually. Due to the nature of technology development it is not entirely clear when technological breakthroughs will occur to allow the technology to move to commercialization. However, it can be assumed that total RD&D funding will continue at present levels until the required breakthroughs are achieved.

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[11] Ogden, Joan. AB1007 Conference Call

[12] CEC, 2005 IPER; *Forecasts of California Transportation Energy Demand*, April 2005.

II. Present Deployment

Presently, multiple major automakers are demonstrating FCVs by placing prototype vehicles into the field. To date, none have built more than 100 FCVs over the life of their development programs, and not many more than 300 vehicles have been produced by all the major automakers, combined.[13] Nevertheless, the ongoing development at the OEMs is leading to increasing numbers of prototypes on the road each year. The automakers, along with fuel cell developers, tank manufacturers, national labs, and universities are all working diligently to surpass the technological and cost barriers that are holding back introduction of fuel cell vehicles.

In addition to the technical barriers (Section III) hindering FCV deployment, many OEMs state that the most significant issue with FCVs "is the lack of a hydrogen infrastructure, and the lack of a firm commitment to build one."[14] At present, the hydrogen infrastructure in California consists of 11 private fueling stations, with plans from public agencies and private industry to increase that number to 39. Most of these stations are used to test fueling procedures and may be the base for hydrogen fleets as vehicle production enters the pre-commercialization stage. The *Blueprint Plan for the Hydrogen Highway Network* outlines a multi-phase plan to build-out the infrastructure to include 250 stations serving 20,000 vehicles. Presently, Phase 1 is moving forward and should yield a total of 50-100 stations statewide serving 2,000 LDVs from major manufacturers. In addition to the California Hydrogen Highway, some DOE-sponsored projects are attempting to determine an optimal method for building hydrogen infrastructure in the transition period (0-10% vehicle penetration). These models analyze the best ways to build infrastructure for cities, regions, and the entire U.S. As of yet no commitments have been made by government or industry to construct a hydrogen infrastructure on any scale larger than that presented by California in the *Blueprint Plan for the Hydrogen Highway Network*. The development of this larger infrastructure is one of many significant barriers that must be overcome to deploy hydrogen FCVs on a large scale.

III. Penetration Scenarios

Estimating the future penetration of hydrogen fuel cell vehicles (FCVs) and the related effects on energy consumption, petroleum dependency, and GHG reduction is extremely speculative due to the numerous technical barriers that are impeding progress to mass-production of FCVs. It is presently unclear exactly how long, or how expensive, it will be to reach many of the technical targets that must be met. Nevertheless, certain OEMs have made predictions as to when FCVs will first be available for public consumption.

Regarding FCVs, Larry Burns, GM Vice-President of R&D, stated that "I don't know how many of them we'll make at the time, but we should have them in showrooms by

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[13] California EPA/ARB, ZEV Technology Review, April 20,2007. pg. 145.
[14] California EPA/ARB, ZEV Technology Review, April 20,2007. pg. 150.

early next decade, around 2011 or 2012. Post-2012, the goal is to ramp up production to about a million vehicles a year, worldwide."[15] Mr. Burns gave no indication of the price for the first "showroom" vehicles. It is likely that cost-competitive vehicles will not be available for a few years following the initial showroom deployment.

Honda also speculated on deployment dates, stating that by 2018 hydrogen FCVs will be available to consumers at costs comparable to standard luxury vehicles.[16]

The penetration scenarios shown in Figure 1-1 reflect estimates from three California studies: the California EPA's *Blueprint Plan for the Hydrogen Highway Network* (2005), UC Berkeley's technical analysis of *A Low-Carbon Fuel Standard for California* (2007), and the California EPA and ARB's *ZEV Technology Review* (2007). These scenarios are driven by estimates of when hydrogen FCV production will reach major milestones, such as pre-commercialization, low-volume commercialization, and mass-commercialization. The various estimates were evaluated to determine which might be representative of two potential scenarios: a business-as-usual scenario (BAU) and an aggressive growth scenario (AGG). The milestone dates for the various scenarios are shown in Table 2-1. While the projections are shown to 2050, not all of the available studies provided estimates that far in the future, so estimates were made to continue the projections to 2050. The low-growth scenario is based on estimated dates for commercialization milestones produced by the *ZEV Technology Review* expert panel.[17] The annual sales specified by the *ZEV Review* are similar in magnitude to the estimates in the "business-as-usual" scenario published in *A Low-Carbon Fuel Standard for California* which only projects to 2020[18]. Further predictions of milestone years for the low-growth scenario are estimates of TIAX. The aggressive case is based on the electric-drive scenario (C5) published in *A Low-Carbon Fuel Standard for California*.[19] This scenario is indicative of a situation in which effort is focused on the development of electric drive-train vehicles: HEVs, PHEVs, EVs, and FCVs. The electric-drive scenario makes predictions through 2020. Again, additional projections beyond 2020 are TIAX estimates.

Table 2-1: Hydrogen LDV Penetration Milestones

		Scenario Years*	
Vehicle Technology Status	**Vehicles/year (Global)**	**BAU**	**AGG**
Demonstration	100	2008	2008
Pre-Commercial	1,000	2009	2009
Low-Volume Commercial	10,000	2020	2012
Mass-Commercialization	100,000	2025	2015
Million Vehicles	1,000,000	2055	2045
		10% of production FCVs sold into	100% of FCVs sold into California

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[15] Reuters, May 15, 2007. www.reuters.com/article/environmentNews/idUSN1546743220070516?feedType=RSS

[16] Interview with Stephen Ellis, Honda

[17] California EPA/ARB, *ZEV Technology Review*. pg. 7.

[18] Farrell & Sperling, *A Low-Carbon Fuel Standard for California*, May 2007, pg. 118.

[19] Farrell & Sperling, *A Low-Carbon Fuel Standard for California*, May 2007, pg. 123.

As stated earlier, the fulfillment of any of these scenarios is highly dependent on the timing of enabling breakthroughs.

IV. Technological Barriers

Given the financial commitment demonstrated by industry and government, the primary barrier to mass-commercialization of hydrogen FCVs is the technical challenge required to develop the necessary equipment at appropriate cost targets. Additional time, money and research is required if these objectives are to be achieved. To date it appears as though this research will continue until the goal of commercial FCVs is realized. The primary technological barriers are generally associated with on-board hydrogen storage, the fuel cell power system, and the development of a hydrogen infrastructure.

On-Board Hydrogen Storage

As stated by the California ARB/EPA *ZEV Review*, "the cost, weight, and volume of adequate on-vehicle hydrogen storage…remain major barriers to commercialization."[20]

The requirement for hydrogen storage depends primarily on the desired vehicle range. Traditionally, all LDVs from major manufacturers have a range of 300-miles or more between vehicle refills. The Department of Energy, working with industry, has selected hydrogen storage targets for 2015 that correspond to a 300–mile vehicle range. It is presumed that vehicles unable to achieve a 300-mile range will not result in a successful consumer vehicle.[21]

In the near-term most OEMs intend to use compressed hydrogen storage to achieve these goals; however, compressed storage has problems providing sufficient range without excessive weight, volume and cost. A major problem is that the low volumetric energy density of compressed hydrogen makes it difficult to store a sufficient supply on-board the vehicle. The relative volumetric energy densities of various fuel options (compresses hydrogen, liquid hydrogen and gasoline) are shown in Figure 4-1.

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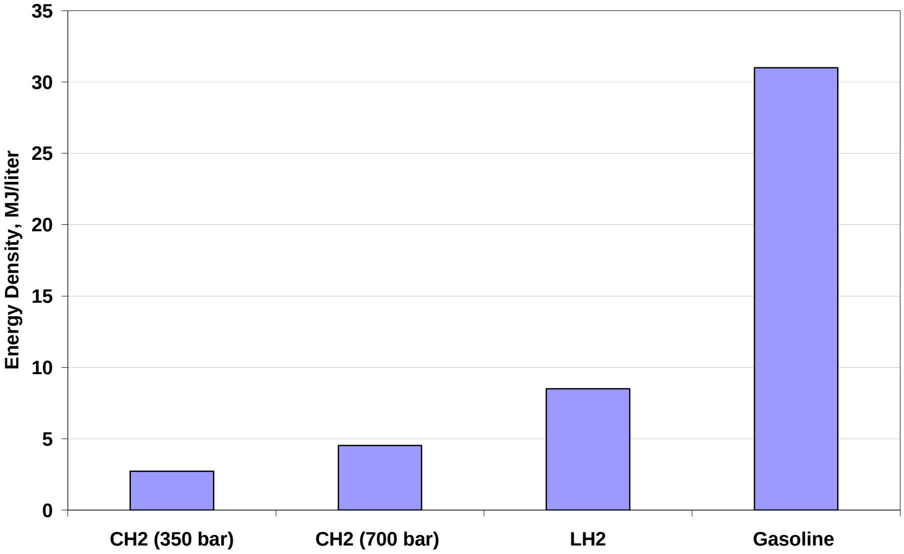
[20] California EPA/ARB, *ZEV Technology Review*, pg. 8.

[21] California EPA/ARB, *ZEV Technology Review*, pg. 66.

Figure 4-1: Volumetric Energy Density[22]



While compressed hydrogen (700 bar) has only 15% of the energy density as gasoline, the volume storage requirements are not as severe due to the energy efficiency ratio (EER) improvements inherent in using a fuel cell as a prime mover. The FCV EER of 2.0 (meaning that a FCV is twice as efficient as its gasoline counterpart) effectively reduces by 50% the amount of fuel-borne energy needed on-board to achieve the desired range. Despite these EER benefits, compressed hydrogen will still require significantly larger tanks than comparable gasoline vehicles. Most auto manufacturers prefer the use of 700 bar hydrogen storage for obvious range and storage issues. Tank manufacturers have yet to build tanks at either pressure rating that are within the cost goals set forth by the DOE. The cost goals and present status are specified in Table 4-1:

Table 4-1: Volumetric Energy Density[23]

Tank Type Pres. Rating	Cost ($/kWh)	
	Present	DOE Goal
CH2 Tanks (350 Bar)	10-12	4 (2010) 2 (2015)
CH2 Tanks (700 Bar)	13-15	4 (2010) 2 (2015)

Given present costs, a 5 kg (1 kg = 33.3 kWh ≈ 1 gal. gasoline on an energy basis) tank – which will likely be sufficient for a 300-mile range[24] – is expected to cost no less than $1,650. At low volumes the cost of compressed hydrogen tanks are estimated to be $10,000 or more. The *ZEV Review* states that "without a major breakthrough, no major

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[22] AB1007, WTT Report, TIAX 2007

[23] California EPA/ARB, *ZEV Technology Review*, pg. 149.

[24] 300 miles/5kg = 60 miles/kg ≈ 60 mpgge, from TIAX analysis of EPA certification data and vehicle modeling results

improvement in these cost levels is foreseen at this time." Weight projections indicate that compressed storage can meet the 2010 target weight fraction of 6%, but cannot meet the 2015 target of 9%.[25]

Liquid storage is not-likely to be accepted by OEMs in the near-term as there are numerous difficulties associated with the low-temperature required to keep hydrogen in the liquid phase. In addition, liquefaction is a highly energy intensive process, thus significantly reducing the WTW energy and GHG benefits of FCVs. Research is on-going into alternative storage techniques (metal or chemical hydrides, activated carbon structures) that may lead to improved gravimetric and/or volumetric energy densities. Despite the inherent potential benefits of these alternative carriers, it is too early to make accurate predictions as to their deployment and cost.

Automotive Fuel Cell

While the automotive fuel cell has not yet reached the performance or cost goals required for commercialization, there continues to be substantial progress made towards commercially viable products. Despite this progress, there is consensus among fuel cell system developers that commercialization will require the simultaneous achievement of[26]:

- Higher power per unit area membrane electrode assemblies (goal of 0.8-1.0 W/cm^2)
- Reduced catalyst loading/cost (goal of <0.1-0.5 mg_{Pt}/cm^2)
- Longer operating life and improved durability (goal of >5000 hrs)
- PEM materials that are stable and can operate to 100°C

The estimated time required to meet these targets varies between developers, with some stating 2010 given production of 500,000 units annually and others 2020 at volumes of 100,000 units.[27] The *ZEZ Review* panel remains "cautiously optimistic" that these barriers can be overcome in 5-10 years. Table 4-2 illustrates the goals and present status of automotive fuel cell development.

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[25] California EPA/ARB, *ZEV Technology Review*, pg. 150.
[26] California EPA/ARB, *ZEV Technology Review*, pg. 129.
[27] California EPA/ARB, *ZEV Technology Review*, pg. 130.

Table 4-2: Hydrogen Fuel Cell Goals and Status[28]

Fuel Cell Power System[1] Parameter	FreedomCAR Goals	Present Status[2]	Forecasted Status[2] (2015)
Lifetime (years)	15	2-3	10-13
Peak Efficiency (%)	60	50-60	60
Gravimetric Power Density[3] (W/kg)	325	300-500	700-1100
Volumetric Power Density[3] (W/l)	220	N/A	N/A
Cost[4] ($/kW)	$40 (2010) $30 (2015)	$75-$600	$30-$75

1. Consist of fuel cell stack, the fuel cell stack auxiliary sub-systems (e.g. sub-sytems for air supply, fuel supply, thermal management, and any other necessary functions, such as water management), the hydrogen storage system, the high-voltage energy storage system (if used) , and all encloseures and connections.
2. Assessment of EPA/ARB ZEV Review Panel
3. Excluding hydrogen storage
4. Direct material/labor and production facility costs. Indirect costs, marketing and profit not included. Design level assuming 250,000 units per

The RD&D cost necessary to achieve the goals shown in Table 4-2 is unknown, but it is assumed that expenditures will continue at the present rate, or increase, in the near–future. Development of hydrogen FCVs is supported by the Hydrogen Fuel Initiative that was presented by the President in his 2003 State of the Union.[29] This program committed $1.2 billion between 2003 and 2008 (2007: $289 million, 2008: $309 million). It is assumed that most of these funds are leveraged with a 50/50 cost-share from industry. Thus it is estimated that the overall U.S. expenditures for RD&D exceed $600 million annually. Hydrogen projects are also funded by California and numerous other states and organizations, increasing the overall investments in hydrogen.

Hydrogen Infrastructure

As stated in the Executive Summary, hydrogen is presently produced in large quantities for industrial – particularly refining – applications and is often transported by pipeline. Figure 1-3 illustrates that relative amount of hydrogen required to supply the various penetration scenarios and the present U.S. domestic production. For the aggressive case, California would require approximately a 25% increase in domestic production. While significant, this increase is not insurmountable for a market in which multiple companies produce large quantities of hydrogen. The larger issue that needs to be addressed is the creation of a hydrogen distribution infrastructure.

The lack of an existing hydrogen infrastructure is a major barrier to the use of hydrogen as a transportation fuel. In California there exist 11 hydrogen fueling stations that are

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[28] California EPA/ARB, *ZEV Technology Review*, pg. 13.

[29] Bush, George W. *State of the Union*, 2003. http://www.whitehouse.gov/news/releases/2003/01/20030128-19.html

generally private facilities used for RD&D purposes. Significant development must occur in order to create a network large enough to support even pre-commercial FCV deployment.

The potential methods of hydrogen production and distribution are numerous, but a main differentiating factor between hydrogen stations is whether the hydrogen is generated on-site or at a central facility. In the case of central generation, hydrogen can be distributed by truck or pipeline; however, it is assumed that pipeline networks will not be installed until there is significant market penetration - generally assumed to be more than 10% of vehicle population.

California is moving forward with plans to create a hydrogen infrastructure consisting primarily of stations with on-site generation. The California Hydrogen Highway Network[30] is a multi-phase plan aimed at installing a hydrogen infrastructure as indicated below:

- Phase 1 will install 100 hydrogen fueling stations in major urban areas intended to serve 2,000 light-duty vehicles (LDVs) and 10 heavy-duty vehicles (HDVs)
- Phase 1 stations will primarily serve fleet vehicles operated by the State of California, other government agencies, and private companies and individuals with vested interests in hydrogen vehicles
- For most stations in Phase 1, hydrogen will be generated on-site using various methods including: SMR, electrolysis, and high-temperature fuel cell energy stations
- Some stations will receive delivered hydrogen as either a liquid or compressed gas
- Total cost of Phase 1 infrastructure development: $65.0 million (cost for 61 stations, as 39 are already built or planned as part of existing programs) which will be cost-shared on a 50/50 share between the state government and industry
- Phase 2 will increase the number of stations to 250, for a vehicle population of 10,000 at a total cost of $76 million
- Phase 3 will not construct any additional stations, but will see the utilization of the 250 stations increase significantly such that the stations will serve 20,000 vehicles

Beyond the California Hydrogen Highway, additional stations with varying capacities and production/delivery methods will be constructed to meet demand. Numerous models have been, and are continually being developed to predict the transition scenario to hydrogen and the cost associated with that transition. This is a difficult task especially given the disconnect between the models optimizing large scale implementation plans, government willingness to coordinate this development, and the various energy and industrial gas companies that will likely own and operate fueling stations. For this analysis, it was assumed that large (1,500 kg/day) on-site generation stations would be constructed to meet the increasing demand, with each station serving 2,250 vehicles.

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[30] California EPA, *California Hydrogen Blueprint Plan*, 2005.

Despite the financial and technical barriers to implementation there are many reasons to believe that hydrogen FCVs will develop to a point of commercially viability.

V. Hydrogen Fuel Cell Vehicle Benefits

For many automobile manufacturers, the adoption of hydrogen fuel cell vehicles (FCVs) is “the ultimate solution to reducing both criteria pollutants and climate change emissions.”[31] This position is supported by the President’s Hydrogen Fuel Initiative which supports numerous DOE hydrogen and fuel cell programs, as well as the “massive efforts by the major fuel cell developers and automobile manufacturers”[32] that have resulted in “impressive advances in every aspect of fuel cell technology.”[33] The numerous benefits that will be realized with the commercialization of FCVs are the driving force behind the investment in and commitment to FCVs.

Zero-Emission Vehicles

The use of hydrogen as an on-board energy carrier provides the opportunity for truly zero-emission vehicles. ZEVs are defined by the California EPA and ARB as vehicles that have zero emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM), which are the main contributors to air pollution. In addition, the compliance with these requirements cannot change with age or maintenance, and an increase in total fleet mileage cannot increase vehicle emissions.

At this point in time, only two types of vehicles have fulfilled the requirements set forth for ZEVs: full performance battery electric vehicles and fuel cell vehicles that consume on-board hydrogen. Technical barriers presently hinder the mass-commercialization of either type of ZEV.

The consumption of a carbon-less energy carrier is the reason that no formation or emission of HC, CO and PM occurs in a hydrogen powered vehicle. Hydrogen vehicles designed to consume hydrogen in internal combustion engines (ICEs) will still generate NOx due to the high in-cylinder temperature and presence of nitrogen and oxygen as well as small amounts of PM due to oil leakage around piston rings. Consumption of hydrogen in a fuel cell occurs at a low-temperature, therefore there is no opportunity for NOx formation, allowing the hydrogen FCVs to achieve the standards required for ZEVs.

While the criteria emissions standards for gasoline ICE vehicles are quite stringent, the large scale replacement of gasoline vehicles with ZEVs has the potential to significantly reduce overall emissions of criteria pollutants.

Efficiency Benefits

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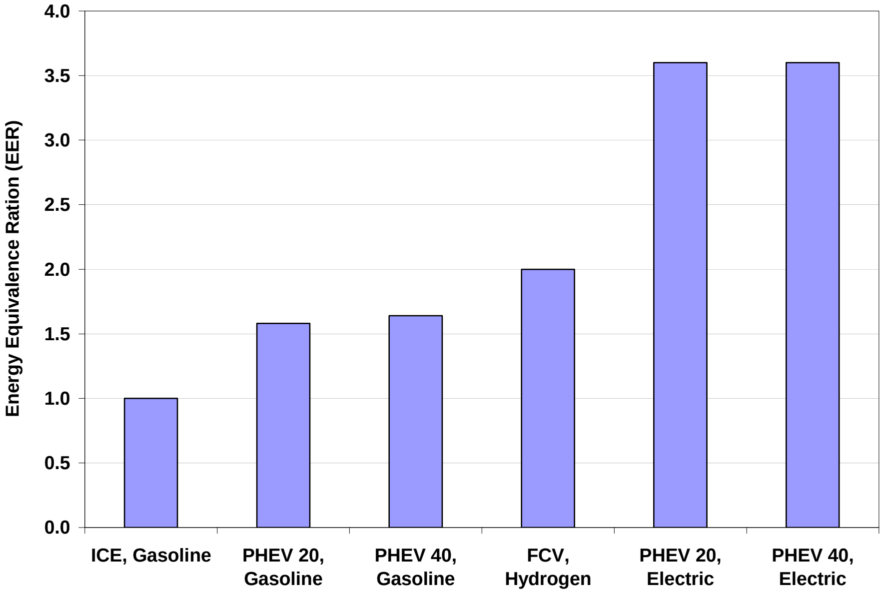
[31] California EPA/ARB, *ZEV Technology Review*, pg. 7.

[32] California EPA/ARB, ZEV Technology Review, April 20,2007. pg. 93.

[33] Ibid.

In addition to achieving the stringent standards required of ZEVs, hydrogen FCVs will have significant efficiency benefits in relation to ICE powered vehicles. While the reactants and products are generally the same for hydrogen use in an ICE or fuel cell, the fuel cell employs a proton membrane to control the reaction, thereby reducing the entropy generation inherent in the chaotic molecular manipulation associated with combustion. In addition to controlling the reaction, the fuel cell directly produces electricity by utilizing the flow of electrons in the cell. By directly creating electricity FCVs can employ efficient all-electric drive-trains without necessitating a generator to convert the mechanical energy of an ICE to electricity. Figure 5-1 illustrates the potential vehicle efficiency improvements that can be realized by using a hydrogen FCV. The EER values shown do not account for any efficiency gains or losses associated with the production and delivery of hydrogen or other vehicle fuels.

Figure 5-1: Vehicle Energy Efficiency Ratio (EER)[34]



It is important to note the overall EER of a PHEV is a combination of the electric and gasoline performance and is highly dependent on the electrical energy consumed between vehicle charging. While it is also necessary to evaluate the full fuel-cycle energy use and GHG emissions to fairly compare different vehicle fuel options, a fuel cell's efficiency benefits are extremely important to reducing overall energy use.

Multiple Feedstocks

As mentioned earlier, hydrogen is unlike many other fuel options because it is not a primary energy source. Unlike crude oil or natural gas, both of which are naturally occurring and refined for use as vehicle fuels, hydrogen must be produced from other more fundamental feedstocks – of which natural gas, for example, is a viable option. Hydrogen is more synonymous with electricity since both are produced, transported, and

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[34] AB1007, *TTW Report*, TIAX 2007.

consumed at the point-of-use. As a result of this characteristic, there are a vast number of energy feedstocks that can be used to produce hydrogen. The overall effect on petroleum reduction, energy consumption and GHG emissions will depend heavily on the process and energy feedstock used to produce hydrogen.

While there are a great number of potential hydrogen production and delivery pathways, three primary production methods are generally considered. They are: electrolysis, reformation, and gasification.

Electrolysis

The electrolysis of water uses electricity to split water into hydrogen and oxygen. When employing electrolysis as a production method, numerous feedstocks – renewable energy sources in particular - can be used. Solar, wind, hydro, and nuclear can all produce the electricity used to electrolyze water and provide hydrogen gas. While electricity from fossil fuel feedstocks (coal and natural gas) can be used in an electrolysis process, it is generally more efficient to use hydrocarbons in a reformation or gasification process. In addition, when using hydrocarbon feedstocks it may be necessary to sequester the carbon dioxide in order to bring full fuel-cycle GHG emissions within acceptable limits. Electrolysis is generally used in conjunction with low-cost electricity or when the demand is insufficient to make a reformer cost effective. Electrolysis is also favorable as a result of the purity of hydrogen that results from the process. The lack of carbon in the water drastically reduces the opportunities for contamination. A significant drawback to electrolysis is the large energy consumption that leads to a WTT efficiency of 32.9% (assuming the use of grid-mix electricity).[35] Despite this significant drawback, electrolysis may play a large role in hydrogen production due to the ability of generating hydrogen from renewables such as wind which often provide peak power during off peak power demands (at night).

Electrolysis is a production technique that can be installed in large production facilities or small distributed generation sites.

Reformation

When discussing hydrogen production, reformation generally refers to steam-methane-reformation (SMR), which is a method for producing hydrogen from natural gas. On an industrial scale, SMR is the dominant method of hydrogen production as it is generally accepted to be the most inexpensive. Reformation mixes steam and natural gas at high temperatures over a catalyst that allows for reactions to produce a syngas of carbon monoxide and hydrogen. Additional water can be added to shift the remaining carbon monoxide to carbon dioxide and additional hydrogen.

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[35] AB1007, *WTT Report*, TIAX 2007.

SMR is generally a process that can be employed at either a central production facility or on-site at distribution facilities. The high ratio of hydrogen to carbon in the original feedstock (natural gas) reduces the need for sequestering the carbon dioxide emissions as it will likely have favorable full fuel-cycle GHG emissions when compared to many other hydrocarbon fuels.

Gasification

Gasification is a process which converts various materials including coal, petroleum-based substances, and biomass into a syngas having a variety of components, including methane, hydrogen, carbon monoxide, and carbon dioxide. This transformation is achieved using a process that involves heat, pressure and steam. The amount of steam required is dependent upon the ratio of hydrogen and carbon in the feedstock, but is generally significant as much of the hydrogen produced originates from the steam injected into the gasifier. The gasification process takes place in a reaction chamber – a gasifier – into which the feedstock is fed in dry or slurry form. Gasification generally occurs in an environment that is either oxygen free or oxygen deprived to minimize the creation of combustion products: water and carbon dioxide. Following the gasification process the syngas must be shifted and purified (a similar process to reformation) to create an outlet stream of hydrogen with purity sufficient for use in the highly sensitive PEM fuel cell. Biomass is the primary renewable source that produces hydrogen in a gasification process. The use of coal or petroleum products may require sequestration to meet stringent GHG emissions targets.

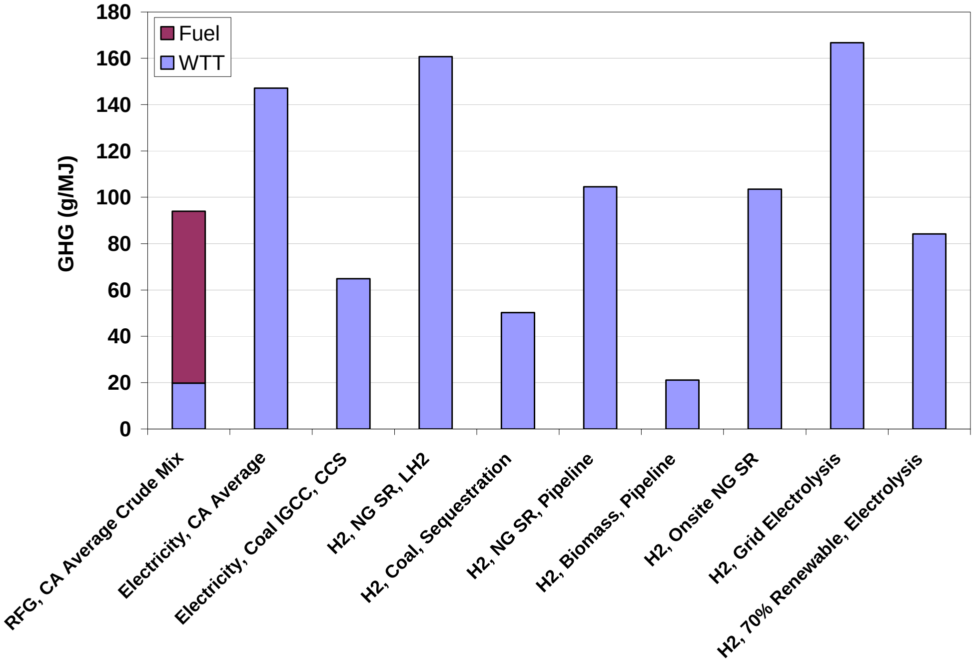
Gasification will generally be a method only used in central production due to the complexity and scale required for much of the gasification equipment.

Other Production Methods

Other hydrogen production methods include thermochemical water splitting which use heat generated by nuclear plants or concentrated solar to split water into hydrogen and oxygen, but these technologies are still in the research and development phase. Also being researched is the use of biochemical processes that make use of living organisms to produce hydrogen.

All of the potential hydrogen sources have different well-to-tank emissions, which include all of the emissions from resource extraction/generation, hydrogen production, and deliver. The upstream GHG emissions for fuel production and delivery are shown in Figure 5-2.

Figure 5-2: Fuel Specific WTT GHG Emissions[36]



It is interesting to note that gasoline compares favorably with many fuels on a GHG per unit energy basis. It is, however, hindered by the relative inefficiency of the ICE and mechanical drivetrain on conventional vehicles, as illustrated in Figure 5-1. In comparing the well to wheels estimates for the above hydrogen production options one can multiply the hydrogen WTT numbers by 0.50 to account for the improved efficiency of the fuel cell vehicles compared to conventional ICEs.

Vehicle Attributes

Given the high incremental cost of FCVs, it is highly unlikely that tax credits or other incentives will allow them to be cost-competitive with traditional gasoline ICE vehicles. As a result, FCVs will need attributes that incent prospective buyers to choose FCVs over other options. Numerous favorable attributes exist.

A major benefit is the adoption of a non-fossil, low-carbon fuel. By adopting a fuel that can be produced from multiple feedstocks, the consumer is no longer subject to the price volatility of the fossil-fuel market. The global political situation and decreasing petroleum reserves both serve to increase the likelihood of large gasoline price fluctuations. In addition to protection from price volatility, the use of a low-carbon fuel may pay financial rewards in a carbon-constrained economy. The adoption of carbon limits and/or a cap-and-trade system will favor those consumers using the most carbon-neutral fuel available. The large variety of feedstocks allow for the optimization of feedstock cost and carbon intensity, leading to a financially efficient fuel under carbon regulations.

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[36] AB1007, *WTT Report*, TIAX 2007.

The variety of hydrogen feedstocks also benefits the auto manufacturers by decoupling their future business from the volatility of the petroleum market. With declining crude supplies, it wise for auto manufacturers to develop technologies that will allow consumers to purchase vehicles not dependent on gasoline. It appears that for the auto makers, FC development is a large hedge against a future of high oil prices. Many OEMs are investing hundreds of millions of dollars in FCV development which reveals their belief that FCVs are vitally important to their long-term viability.

Fuel cell vehicles may also take advantage of the ability for home refueling and energy integration. The natural gas industry has begun to promote home refueling, using the Phill, a system that compresses and distributes natural gas to vehicles in personal homes. Home refueling offers the potential for favorable energy prices as well as the convenience of not having to travel to fueling stations – particularly beneficial in a developing infrastructure. Honda, a manufacturer of natural gas vehicles (NGVs) and distributor of the Phill, envisions similar benefits from the development of hydrogen home refueling. Hydrogen home refueling units would reform natural gas to produce hydrogen for use in FCVs. Beyond home refueling; Honda is developing a home energy system that will use natural gas in a tri-generation system to produces electricity, heat, and hydrogen. With the development of such a technology, the adoption of a FCV has implications that could favorably affect other facets of energy use and cost in the home.

Using FCVs as the prime mover and removing the ICE allows OEMs to offer fundamentally different vehicle platforms. GM's AUTOnomy concept is a good example of the flexibility that FCVs may give automobile designers to improve styling, aerodynamics, and interior layout. The AUTOnomy features a skateboard-like chassis, shown in Figure 5-3, into which the fuel cells and electric motors are packaged. The development of a single chassis offers the OEMs the ability to produce a variety of vehicles from one platform, potentially reducing production costs.

Figure 5-3: GM AUTOnomy Concept Skateboard Chassis[37]

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[37] http://www.fueleconomy.gov/feg/fc_pics/GM_AUTOnomy_FC_Chasis3D_angle.jpg

Hydrogen vehicles also offer the benefit of reduced vehicle noise, as well as the potential for travel benefits, including access to California’s High Occupancy Vehicle (HOV) lanes.

VI. Summary of Penetration and Cost Assumptions

- **Vehicle Penetration:**

		Scenario Years*	
Vehicle Technology Status	**Vehicles/year (Global)**	**BAU**	**AGG**
Demonstration	100	2008	2008
Pre-Commercial	1,000	2009	2009
Low-Volume Commercial	10,000	2020	2012
Mass-Commercialization	100,000	2025	2015
Million Vehicles	1,000,000	2055	2045
		10% of production FCVs sold into	100% of FCVs sold into California

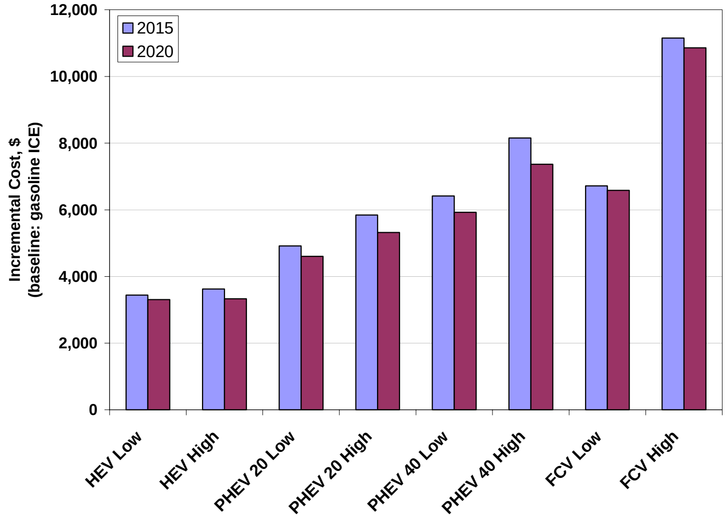
  - Business-as-Usual: Corresponds with production volumes estimated by *ZEV Review*, assuming 10% of FCVs are sold into the California market
    - The LCFS business-as-usual case is similar to that in the *ZEV Review*
  - Aggressive Growth Scenario: Corresponds with LCFS "Electric Vehicle" case, and assumes that 100% of vehicles are sold into the California market – this assumption is required to keep global production levels at reasonable levels
  - Vehicle Lifetime: 10 years, with retirement for all vehicles occurring at 10 years (i.e. – no scrappage curve was used)

- **Fuel Cell, Hydrogen Storage and Vehicle Costs**
  - Fuel cell costs between \$30-75/kW (*ZEV Review*, pg. 149)
  - Power requirement: 87 kW, which is the average FC power in demonstration vehicles (*ZEV Review*, pg. 142)
  - Hydrogen storage (700 bar) costs between \$13-15/kWh (*ZEV Review*, pg. 149)
    - No significant cost reduction is anticipated (*ZEV Review*, pg. 150)
    - At low volumes hydrogen storage tanks may costs as much as \$10,000
  - Storage requirement: 167 kWh, which is based on 5 kg for 300 mile range
  - Fuel cell and storage costs were added to the incremental cost of an HEV, subtracting cost for ICE (\$1,400) and gasoline storage (\$100)
    - Incremental HEV costs:

	2015	**2020**
HEV Low	\$3,443	\$3,309
HEV High	\$3,627	\$3,333

(source: *Dean Taylor*)

    - Incremental cost for electric vehicles:



- These incremental costs apply only to mass-produced vehicles, which is assumed to be production volumes greater than 100,000 units/year (TIAX estimate)
- Incremental FCV costs for production volumes less than 100,000 assumed to be $15,000 for the low case and $30,000 for the high case (TIAX estimate based on low-volume storage vessels costing up to $10,000/unit)
- Vehicle costs discounted with a discount rate of 10%

- Hydrogen Station Infrastructure
  - Station infrastructure follows costs presented by the *Blueprint Plan for the Hydrogen Highway Network* until California vehicle population is greater than 20,000 vehicles

Infrastructure Technology Status	Vehicle Population	Total Stations	Phase Cost	LOW	MOD	AGG
California HH Phase 1	2,000	100	107,000,000	2017	2016	2008
California HH Phase 2	10,000	250	76,000,000	2024	2022	2010
California HH Phase 3	20,000	250 (high util.)	0	2028	2024	2012

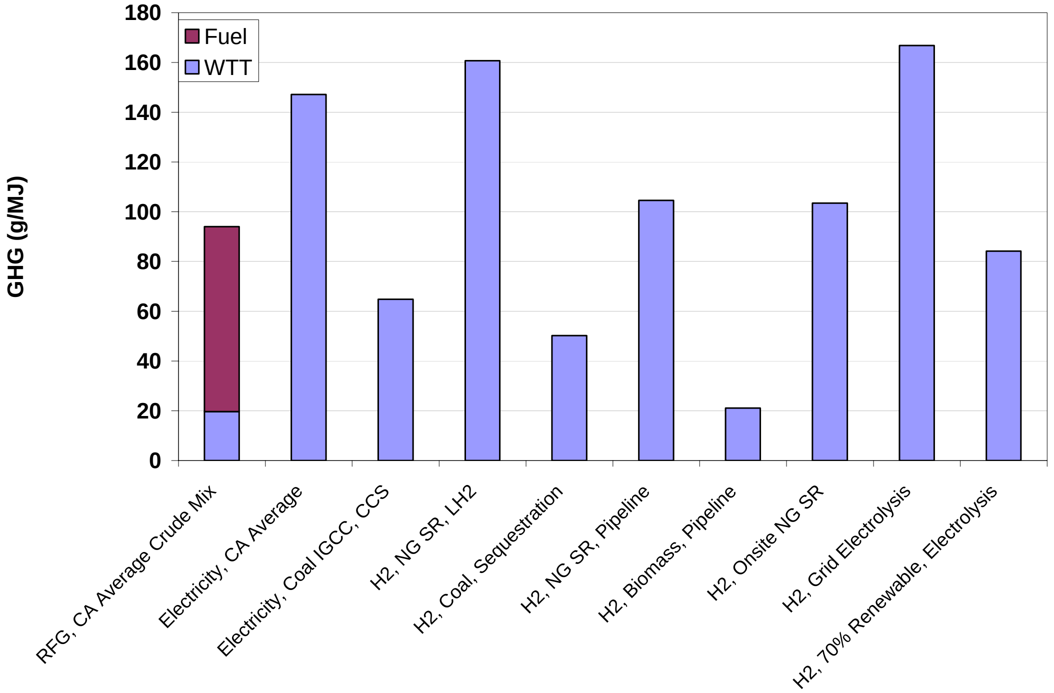
(*Blueprint Plan for California Hydrogen Highway Network*)

  - For vehicle populations greater than 20,000 vehicles, 1,500 kg stations are added to the network
    - Each 1,500 kg station serves 2,250 vehicles
    - Each 1,500 kg station has a capital cost of $3,225,136 (*H2A, 1,000 kg/day on-site SMR station*)
  - Infrastructure costs discounted with a discount rate of 10%

- Fuel Economy and Emissions
  - Annual VMT: 14,900/vehicle
  - Baseline gasoline fuel economy: 30.3 mpg
  - Advanced gasoline fuel economy: 43.3 mpg
  - Gasoline LHV: 41.5 MJ/kg
  - Gasoline density: 2.828 kg/gal

- CO2 content of gasoline: 8.72 kg/gal.
- FCV EER: 2.0
- PHEV 20 (Electric) EER: 1.58
- PHEV 20 (Gasoline) EER: 3.60
- PHEV 20, Time in Electric Mode:35.75%
- PHEV 40 (Electric) EER: 1.64
- PHEV 40 (Gasoline) EER: 3.60
- PHEV 20, Time in Electric Mode: 64.30%
- The GHG emissions for each fuel were taken from TIAX's AB1007 WTT report

Figure 1-1: Fuel Specific GHG Emissions



- Fuel Costs
  - Fuel costs are predicted to be between $2-4/kg, which will make hydrogen competitive with gasoline
  - Given the difficulty in predicting future costs of either fuel, the overall fuel cost/savings were not calculated and it was assumed that fuel costs do not factor into the overall cost of the technology

VII. Appendix I

Definitions of Acronyms:

AGG:	Aggressive Vehicle Penetration Scenario
ARB:	Air Resources Board (California)
CH2:	Compressed Hydrogen
EER:	Energy Efficiency Ratio
EPA:	Environmental Protection Agency
DOE:	Department of Energy (U.S.)
FCV:	Fuel Cell Vehicle
GHG:	Greenhouse Gas
HDV:	Heavy-Duty Vehicle
ICE:	Internal Combustion Engine
LDV:	Light-Duty Vehicle
LH2:	Liquid Hydrogen
LOW:	Low Vehicle Penetration Scenario
MEA:	Membrane Electrode Assembly
OEM:	Original Equipment Manufacturer
PHEV:	Plug-In Hybrid Electric Vehicle
R&D (RD&D):	Research & Design (Research, Design & Demonstration)
RFG:	Reformulated Gasoline
SMR:	Steam Methane Reforming
VMT:	Vehicle Miles Travelled
WTT:	Well-to-Tank
WTW:	Well-to-Wheels
ZEV:	Zero Emissions Vehicle

VIII. Appendix II

Definitions of Fuel Production and Delivery Pathways:

Gasoline:

Gasoline	California RFG from a crude mix

Hydrogen:

SMR/LH2	Central natural gas reformation and LH2 delivered by truck
Coal w/CCS	Central coal gasification w/ carbon capture & sequestration
SMR/Pipeline	Central natural gas reformation and pipeline distribution
Biomass/Pipeline	Central biomass gasification and pipeline delivery
On-Site SMR	Natural gas reformation at hydrogen fueling station
Grid Electrolysis	Electrolysis w/ grid mix elec. at hydrogen fueling station
70% Renew. Electrolysis	Electrolysis w/ 70% renew. elec at hydrogen fueling station

Electricity	
Grid Electricity	California electricity from grid mix generation methods
Coal IGCC w/CCS	Coal-fired integrated gasification combined cycle w/CCS