Attachment A
Status of ZEV Technology Commercialization
(Technical Support Document)

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Appendices

1.0 Introduction

At the March 2008 Zero Emission Vehicle (ZEV) regulation hearing, the California Air Resources Board (ARB or the Board) directed staff to consider and redesign the ZEV regulation. In response to the Board's direction, ARB staff conducted a comprehensive review of ZEV technology and will present the review as an informational item to the Board at the December 2009 Board Meeting. The informational item will focus on ARB's vision for the ZEV program as presented in a White Paper including a 2050 greenhouse gas (GHG) analysis and this technical support document (TSD). The rulemaking process associated with ZEV program modifications will take place in 2010.

This TSD serves as a technical reference for the White Paper and staff's assessment of ZEV technology status. This document was developed from data presented in publically available, peer reviewed analyses and reports speaking to ZEV technology readiness and commercialization, as well as information obtained and aggregated from confidential stakeholder meetings. In addition, ARB surveyed manufacturers of automotive fuel cells and batteries to assess the technical status of ZEV technology, especially with regard to technology development, performance, timing of commercialization, and costs. The questionnaire pertained to fuel cell and battery technology currently in development, technical goals, technical issues impeding introduction of ZEVs, and commercialization challenges. Specifically, this document relies heavily on reports by the Massachusetts Institute of Technology (MIT), United States Department of Energy (U.S. DOE), Advanced Automotive Battery Conference (AABC), TIAX and Directed Technologies Incorporated (DTI). The objective of this report is to provide a thorough and accurate representation of the current status of ZEV technologies and the projection for ZEV technology advancement in both the near and long term.

California is a world-leader in climate change policy and is responsible for leading GHG emission limiting legislation. Most notable is Assembly Bill (AB) 32, the California Global Warming Solutions Act of 2006, which limits GHG emissions at 1990 level by 2020.[1] In addition, Governor Arnold Schwarzenegger enacted Executive Order S-3-05 requiring 80% GHG emission reduction from 1990 levels by the year 2050.[2] Since the transportation sector accounts for approximately 38% of California's GHG emissions and the passenger vehicle sub-sector accounts for approximately 74% of the transportation sector, it is a substantial challenge to meet the 2050 goals unless a portfolio of low-carbon vehicles are pursued in the near future.

Fossil fuel use and GHG emissions are rising at a significant rate around the globe due to continuous demand for passenger car transportation. With a limited supply of petroleum and potential negative impacts of climate change, the challenge is to counteract growth, reduce fossil fuel consumption, and limit GHG emissions.[3, 4, 5]

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[1] California Assembly 2006. Assembly Bill 32. California Global Warming Solutions Act of 2006, Chapter 488, Division 255, Section 38500. Approved September 27, 2006.

[2] Executive Order S-3-05. Schwarzenegger, Arnold. Governor of the State of California. Signed June 6, 2005.

[3] ARB 2009a. California Air Resources Board, Greenhouse Gas Inventory. http://www.arb.ca.gov/cc/inventory/inventory.htm.

2.0 Zero Emission Vehicle Literature Review

ARB staff conducted a comprehensive literature review to assess the type of ZEVs that will likely appear on roads in the future. All trends expressed in this document are drawn from a variety of peer reviewed and publically available reports.
In order for California to meet its 2020 and 2050 goals, significant reduction of GHG emissions are required. California will need to reduce its GHG emissions by 173 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) emissions in order to reach it's 2020 goal (approximately a 30% reduction from 2020 BAU), and an additional reduction of 340 MMT of CO_2e is needed to reach 2050 GHG goals (approximately a 80% reduction compared to the 1990 baseline level).[3, 5] Multiple reports assess and project the changes that the passenger vehicle sub-sector will need to undergo in order to achieve fuel efficiency increases and GHG emission reduction goals. Most reports concur that it will take a combination of new, advanced technology vehicles and fuels with lower carbon content to transform the passenger vehicle fleet in California.[5, 6, 7]

GHG emission reduction is now a major focus in the automotive industry and is the basis of automakers future production plans. Scenarios estimating the future passenger vehicle technology mix use a life cycle analysis, also known as well-to-wheel (WTW) to assess GHG emissions produced in fuel production, fuel transportation and vehicle operation.

Most reports indicate there is significant potential for fuel economy improvement in the conventional, spark-ignited engine (SIE) and these improvements can be achieved with technology available today.[6, 7] In the past, automakers have made significant advances in fuel economy. However, nearly all gains have been directed toward increasing vehicle size and performance rather than limiting environmental impacts. If California is to meet its long term environmental goals, automotive technical advances need to be directed toward further fuel economy improvements. This will include downsizing and light-weighting in order to increase fuel economy and decrease GHG emissions.[8, 9] MIT estimated that sales-weighted average vehicle weight could be reduced 20% over 25 years and the maximum weight reduction at a plausible cost is 35%.[8] Figure 1 and 2 provide anticipated fuel consumption and GHG emission levels from a range of vehicle technologies for the average mid-size car sold in the United States. Other technologies will increasingly be used to green the passenger vehicle fleet such as auto-start-stop, smaller displacement engines with turbo charge, direct injection, homogeneous charged compression ignition and six-speed automatic manual transmissions.[8]

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[4] ARB 2008. Climate Change Scoping Plan. December 2008. http://www.arb.ca.gov/cc/scopingplan/document/adopted_scoping_plan.pdf.

[5] UCD 2008. Cunningham, Joshua., et al. University of California, Davis (UCD) Institute of Transportation Studies, “Why Hydrogen and Fuel Cells are Needed to Support California Climate Policy”. March 31, 2008. UCD-ITS-RR-08-06.

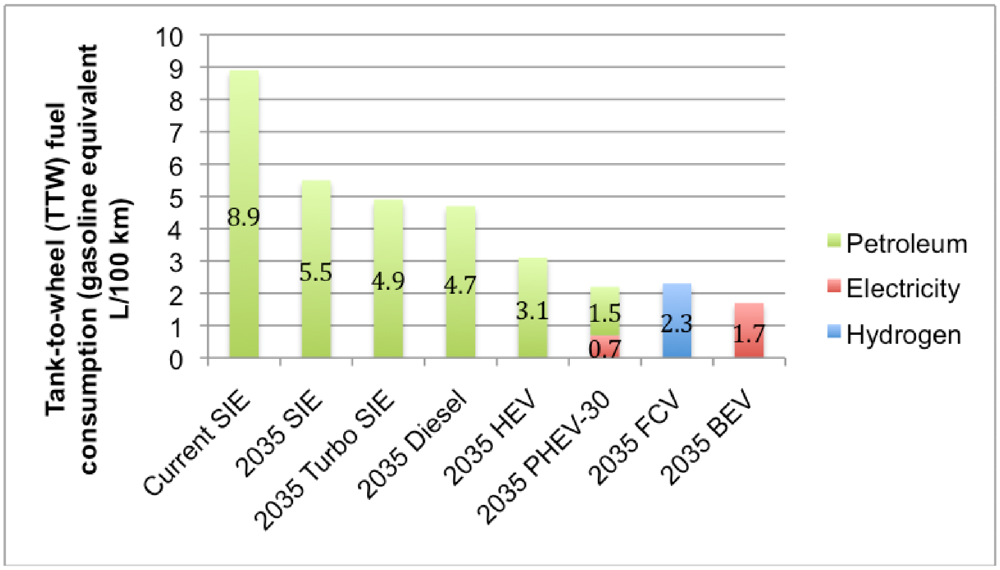
[6] MIT 2008. Bandivadekar, Anup, et al. “On the Road in 2035: Reducing Transportation’s Petroleum Consumption and GHG Emission”. Laboratory for Energy and the Environment. Massachusetts Institute of Technology. July 2008.

[7] American Physical Society 2008. American Physical Society. “Energy Future: How America Can Look Within to Achieve Energy and Security and Reduce Global Warming”. September 2008.

[8] Bandivadekar 2008

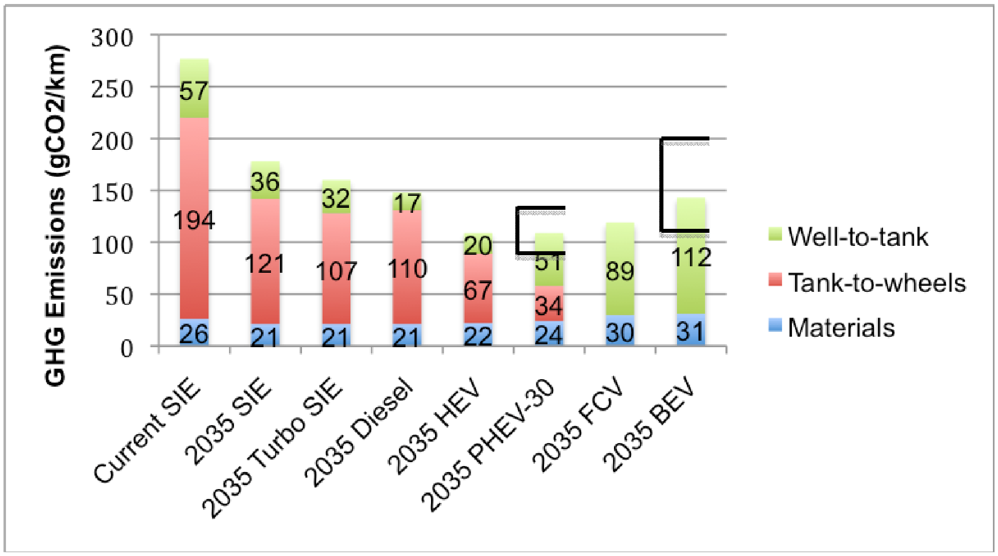
[9] American Physical Society 2008

Figure 1: Tank-To-Wheel Gasoline Equivalent Fuel Consumption



* Data found in MIT “On the Road in 2035” (MIT 2008)

Figure 2: Lifecycle Greenhouse Gas Emissions



* Data found in MIT “On the Road in 2035” (MIT 2008)

Figure 1 and 2: Vehicle propulsion technology assessment for mid-size U.S. passenger cars. Well-to-tank energy consumption is not shown in (a) for different fuel sources, but (b) shows the contribution of well-to-tank energy use in terms of GHG emissions. All vehicles have same performance and interior size. 2035 vehicles have more efficient transmissions, 20% lower weight and reduced drag and tire resistances. Uncertainty bars denote well-to-tank GHG emissions for electricity generated from coal (upper bound) and natural gas (lower bound). FCV well-to-tank GHG emissions assume the hydrogen fuel is steam-reformed from natural gas at distributed locations and compressed to 10,000 psi. SIE = Spark-ignition engine vehicles / HEV = Hybrid electric vehicle / PHEV-30 = Plug-in vehicle / PHEV-30 = Plug-in with 30 mile all-electric range / FCV = Hydrogen fuel cell vehicle / BEV = Battery electric vehicle / Materials = Material lifecycle emissions.

Future efficient gasoline SIE vehicles have the cheapest cost differential compared to future advanced propulsion technology vehicles. It is projected that automaker’s will continue to perfect and produce conventional internal combustion engine (ICE) vehicles for several decades. As shown in Table 1 below, the incremental price difference between an efficient, 2035 gasoline SIE vehicle and a 2007 gasoline SIE vehicle is projected to be $2,600. These vehicles offer significant efficiency gains and GHG emission benefits at the cheapest price point. While smaller, more efficient ICE vehicles will continue to be deployed, ZEV technologies are essential to achieve deep GHG emission reductions. In addition to efficient ICE vehicles, automakers will more than likely increase electrification of their fleets.[10] The gasoline hybrid electric vehicle (HEV) is a promising pathway to cost-effective reduction in fuel use and GHG emissions.[10] The price differential between a 2035 HEV and a 2035 gasoline SIE vehicle is projected to be $2,500 (Table 1). In the near-term, automakers will likely produce small, more efficient conventional ICE vehicles and rapidly hybridize their vehicle portfolios.

Table 1: Incremental retail price of current and future propulsion technologies (MIT 2008)

	RETAIL PRICE INCREASE [$2007]	
VEHICLE TYPE		
	Cars	Light Trucks
Current Gasoline SIE* retail price	$19,000	$21,000
Incremental relative to current Gasoline SIE:		
Current Diesel	$1,700	$2,100
Current Turbo Gasoline	$700	$800
Current Hybrid	$4,900	$6,300
2035 Gasoline SIE	$2,000	$2,400
2035 Gasoline SIE retail Price	$21,600	$23,400
Incremental relative to 2035 Gasoline SIE:		
2035 Diesel	$1,700	$2,100
2035 Turbo Gasoline	$700	$800
2035 Hybrid	$2,500	$3,200
2035 Plug-in Hybrid	$5,900	$8,300
2035 Battery Electric	$14,400	$22,100
2035 Fuel Cell	$5,300	$7,400

Plug-in hybrid electric vehicles (PHEV) offer unique advantages and disadvantages when compared to fuel cell vehicles (FCV) and battery electric vehicles (BEV). Because PHEVs are powered by both the ICE and electricity from the battery there is less range anxiety associated with PHEVs compared to BEVs. Since PHEVs have dual fuel there is no additional range limitations and only minor changes to fueling infrastructure are required. However, like BEVs the main challenges for PHEVs are increasing storage capacity, reliability, durability, and cost reduction of lithium ion

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[10] MIT 2008

batteries. These are significant hurdles but less daunting than some of the challenges facing FCVs and BEVs. The advantages of reduced range anxiety, adequate initial infrastructure, and GHG emission reduction potential, will likely encourage automotive manufacturers to pursue PHEVs as they also seek to increase electrification of their fleet.[11] MIT estimated that the price differential between a 2035 PHEV and a 2035 gasoline SIE vehicle will be $5,900 (Table 1).

According to MIT, BEVs are estimated to be the most expensive and least price competitive option of the advanced vehicle technologies. MIT estimates the price of a 2035 BEV (200 mile range) at a price premium of $14,400 (Table 1). [12] Thus, a BEV with 200-mile range would require a prohibitively expensive battery pack. However, automakers are pursuing short-range BEVs (<100 miles) and believe these cars will penetrate a segment of the passenger vehicle market. Regardless of range, BEVs are expensive and will require significant societal investment in terms of increase vehicle and infrastructure costs. For this reason, continued battery research and development (R&D) continue in order to reduce cost and increase durability.

Most stakeholders agree FCV technology indicates a high degree of technical and cost uncertainty. Real-world durability and cost is still being evaluated in terms of parity with conventional vehicles. FCVs have seen significant improvements over the last few years. If the rate of advancement continues, FCVs could compete with 2035 gasoline HEV and other conventional technologies. It is estimated that a 2035 FCV would have a price premium of $5,300 over a 2035 gasoline SIE vehicle (Table 1). The more challenging issue is rollout of marketable FCVs in conjunction with low-carbon hydrogen fuel generation and distribution.

Cost is a key factor in determining the probability of alternative fuel vehicle commercialization. Passenger vehicles with turbocharged gasoline engines, diesel engines and HEVs entering the market today are estimated to cost 5% to 30% more than a baseline gasoline vehicle.[12] PHEVs and FCVs would cost 25-35% more than a future gasoline vehicle. Since advanced technology vehicles are more expensive and require new, expensive infrastructure, it is crucial that federal, state and local governments remain committed and consistent in terms of policy development and investment during the early stages. For new advanced technology vehicles to have deep penetration into the passenger vehicle sub-sector, pre-commercialization needs to start now and mass-market commercialization must begin by 2015. [13]

3.0 Hydrogen Fuel Cell Vehicle Status

In 2007, during ARB's most recent ZEV technology review, an independent panel of experts (the Panel) reported findings on the technological status of FCVs and BEVs. Since the 2007 report, considerable efforts by major fuel cell developers and automotive manufacturers have resulted in notable advances in fuel cell technology. The intent of

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[11] PHEVs with greater all electric range will be more expensive than even a short range BEV.
[12] MIT 2008
[13] UCD 2008

this section is to assess current technical advancements in fuel cells and their commercialization readiness.

The Panel concluded that automotive fuel cell technology was progressing but had not yet been proven commercially viable. In 2007, the consensus among the most stakeholders was that the following challenges needed to be overcome to reach commercialization: higher membrane electrode assembly, reduced catalyst loading, increased durability, and proton exchange membrane (PEM) materials that are more stable at extreme ambient operating temperatures - the two greatest challenges being cost and durability.[14]

This automotive fuel cell system review relies heavily on the U.S. DOE, TIAX and DTI independent cost assessments, academic reports and information gathered through stakeholder meetings.

3.1 Fuel Cell System Cost

Even though there has been major technology advances since the Panel's review in 2007, FCVs are still too expensive for commercialization. In order to achieve mass-market penetration in the near future, the U.S. DOE and other industry stakeholders continue to undergo extensive, bottom-up analyses to determine which components of FCVs should be targeted for cost reductions. While most FCV components will be improved over time, research teams are now focused on parts that have the greatest cost reduction benefits. Thus, current research funding and effort surrounds the fuel cell system and its most costly components.

The fuel cell system is composed of two main components: the fuel cell stack and the balance-of-plant (BOP).[15] The fuel cell stack contains multiple components including membrane, catalyst, gas diffusion layer (GDF), membrane electrode assembly (MEA) and bipolar plates. The BOP includes an air management system, fuel management system, thermal management system, and water management system. While the hydrogen fuel tank is an important component, it is not typically included in fuel cell system cost. Thus, the hydrogen tank targets and cost will be address in a separate section. In 2006, the fuel cell stack was $69/kW and the BOP was $36/kW. As stack costs have decreased, the BOP components account for a greater percentage of the costs. In 2008, the stack was estimated to have decreased to $34/kW and $37/kW for BOP. Presently, according to the U.S. DOE, fuel cell system cost has been determined to be $61/kW as shown in Table 2[16]. The 2009 cost estimates are more than a 16% reduction in one year and over a 75% reduction since 2002. These cost projections were validated by an independent panel and are widely accepted by industry as a good cost estimate for high-volume production.[17]

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[14] Kalhammer 2007. Kalhammer, Fritz R., et al. "Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Review Panel 2007".

[15] U.S. DOE 2009c. Satyapal, Sunita. "Hydrogen Program Overview". Annual Merit Review and Peer Evaluation Meeting. May 18, 2009, Arlington, Virginia.

[16] U.S. DOE 2009e. Spendelow, Jacob and Marcinkoski, Jason. "DOE Hydrogen Program Record # 9012". October 7, 2009.

[17] NREL, 2009. National Renewable Energy Lab (NREL). "Fuel Cell System Cost for Transportation-2008 Cost Estimate". May 2009.

Table 2 shows the 2008 status of the U.S. DOE FCV validation fleet (140 vehicles) compared to the U.S. DOE 2010 and 2015 targets. Most parameters of the hydrogen fuel cell system are close to meeting the targets. However, the two greatest challenges are fuel cell system cost and durability. In order to the meet the 2010 target, system cost must be reduced approximately 21% and durability must be increased 5 to 6% in real-world validation conditions. Automakers are nearing U.S. DOE targets and continue to push technology toward commercial readiness. For example, the Honda FCX Clarity has demonstrated 2,000 hour durability, a driving range of 240 U.S. EPA real world miles, cold start at -30 C, less than 5 minute refueling and significant volume and weight reductions in the fuel cell stack.[18] The Toyota Highlander (FCHV-adv) fuel cell vehicle can cold start at -30 C, has an estimated >300 mile driving range and has increased stack durability and cost reductions.[19] Toyota plans to continue research and development (R&D) to increase durability and decrease cost for 2015 commercialization. The Daimler B-Class F-Cell has a stack durability of 2,000 hours, range increase of 150%, cold start at -25 C and fast refueling.[20,18] These vehicles are all on the road and demonstrating real-world performance values as the companies push toward meeting the U.S. DOE targets.

Table 2: Current Status and U.S. DOE Targets for Automotive Fuel Cells

	2008 (Current Status)	**2009 (Current Cost Status)**	**2010 Target**	**2015 Target**
System Efficiency	53-58%	N/A	60%	60%
System Cost	$73 k/W	$61 k/W	$45 k/W	$30 k/W
Fuel Cell System Durability	1,900 hours (~57,000 miles)	N/A	2,000 hours (~60,000 miles)	5,000 hours (~150,000 miles)
Vehicle Range	254 miles	N/A	250 miles	300 miles
Fuel Cost	$3/gge	N/A	$3/gge	$2-3/gge
H_2 Quality (purity)	99.73-99.999%	N/A	99.99%	>99.99%
Average Refueling Rate	0.86 kg/min	N/A	1.0 kg/min	1.67 kg/min

3.2 Catalyst

Since the fuel cell stack accounts for 50% of the overall system cost, tremendous effort is underway to reduce individual components within the fuel cell stack. A breakdown of fuel cell system cost by component is provided in Figure 3. The catalyst is the most

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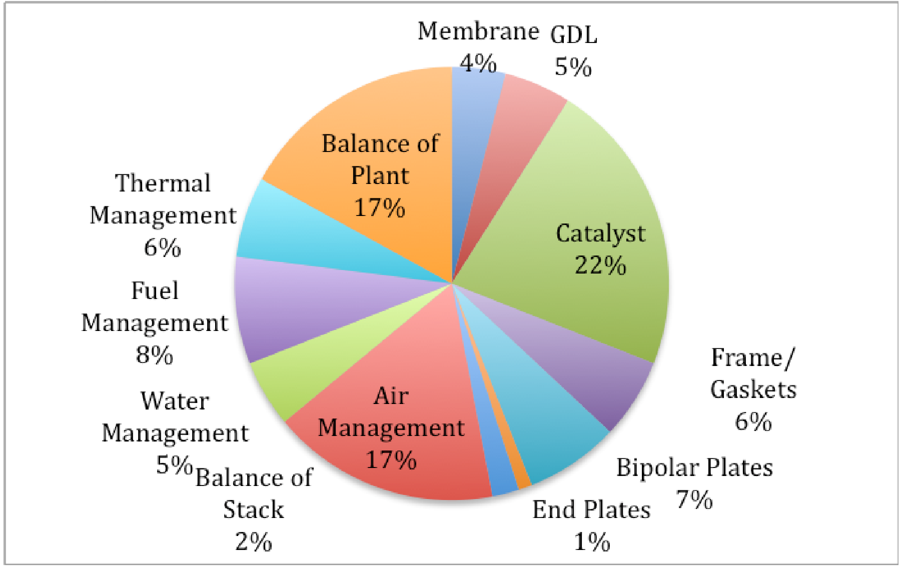
[18] Honda, 2009. Knight, Ben. Honda Motor Company. “Fuel Cell Vehicle Technology Performance and Steps Ahead Presentation”. CARB ZEV Symposium, September 21, 2009

[19] Toyota 2009. Yokoyama, Tatsuaki. Toyota Motor Engineering and Manufacturing North America. “Progress and Challenges for Toyota’s Fuel Cell Vehicle Development Presentation”. CARB ZEV Symposium. September 21, 2009

[20] Daimler 2009. Berretta, Roasario, Daimler. “Fuel Cell Technology for Passenger Vehicles Presentation. CARB ZEV Symposium”. September 21, 2009.

expensive component of the fuel cell system. The platinum catalyst is a precious metal that accelerates the rate of a chemical reaction without itself undergoing any permanent chemical change.[21] Currently, the cost of platinum is $1,100/ troy ounce but this price is very dynamic and fluctuates often.[22] Catalyst research has reduced the platinum group metal (PGM) content from $3,100 at 1.1 g/kW in 2006 to <$600 at <0.2 g/kW in 2008. The U.S. DOE platinum loading targets are 0.3 mg/cm^2 in 2010 and 0.2 mg/cm^2 in 2015 respectively (for an 80 kW stack).[23] Technology advances in the past few years have led to a reduction in platinum loading and an increase in stack power density that significantly contribute to the cost reduction for the fuel cell stack.[24] According to The 2.7 Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model conventional vehicles use 0.0165 lbs of platinum(catalytic converter) and a FCV uses 0.203 lbs of platinum (fuel cell stack). It is estimated that a light FCV uses 0.157 lbs of platinum.[25] In terms of platinum supply, South Africa, Russia and North American are major sources for platinum with South Africa having the largest platinum supply in the world. It is estimated that the total platinum reserves in the Bushveld Complex in South Africa total approximately 1,140 million ounces and a further 387 million are available worldwide. With an annual consumption rate of 5 million ounces of platinum worldwide, it is estimated that existing resources would supply worldwide demand through 2050.[26]

Figure 3: 2008 Fuel Cell Stack Cost by Component



* Data from the National Renewable Energy Lab (NREL) 2009

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[21] Dictionary.com 2009. http://www.dictionary.com

[22] U.S. DOE 2008a. James, Brian, et. Al. “DOE Hydrogen Program Record: Fuel Cell System Cost-2008. December 16, 2008.

[23] U.S. DOE 2009a. Debe, Mark D., “Advanced Cathode Catalysts and Supports for PEM Fuel Cells.” 2009 DOE Hydrogen Program Review. May 2009. http://www.hydrogen.energy.gov/pdfs/review09/fc_17_debe.pdf

[24] U.S. DOE 2008b. Garland, Nancy, et al. “DOE Hydrogen Program Record: Fuel Cell System Cost-2008”. December 16, 2008.

[25] GREET Model. Version 2.7

[26] Cawthorn 1999. Cawthorn, R.G. “The Platinum and Palladium Resources of the Bushveld Complex”. South Africa Journal of Science 95, November-December 1999.

3.3 Hydrogen Fuel Cell Stack Power Density and Weight

While the focus of this document is on cost, it is important to note fuel cell system volume and weight since these factors are essential to better overall vehicle performance and integration. In 2008, the fuel cell system volume was approximately 120 liters and weight approximately 115kg according to the DOE hydrogen validation program. The fuel cell stack alone accounted for 34% of the volume and 40% of the weight. Automakers are reducing stack volume and weight with each fuel cell stack generation. For example, the Honda FCX Clarity's fuel cell stack is 1/5 the weight and 1/4 the volume compared to the previous FCV model.[27] The weight and volume improvements are a result of changes in fuel cell materials (stamped metal flow plates, aromatic membrane structure, reductions in catalyst loading), fuel cell simplification (half the parts, higher recyclability, improved manufacturing) and fuel cell recyclability (light weight and compact, ease of disassembly, materials used, ease of material separation, ease of reprocessing, re-use yield).[24] Other automakers are also reporting significant improvements in weight and size of their fuel cell stacks.

3.4 Hydrogen Tank

The U.S. DOE and industry goal for on-board hydrogen storage is to achieve a vehicle range of greater than 300 miles without compromising passenger space, cargo space and passenger safety in order to facilitate commercialization of FCV across multiple vehicle platforms.[28] In 2009, the U.S. DOE performance targets were revised based on real-world FCV experience. Table 3 shows the old performance targets parallel to the revised targets. Currently, there is no technology that reaches the revised 2015 targets and the new ultimate targets remain very challenging. The new focus is material-based technologies to meet the ultimate target. Metal hydrides, chemical hydrogen storage and hydrogen sorption are all potential options to increase storage and decrease size and cost of the tank. A large number of the second generation U.S. DOE FCVs demonstrated range of 200-250 miles (up from 103-190 miles). The new TIAX cost estimates (at 500,000 units) are $23/kWh for a 700 bar tank which is a 13% reduction in cost compared to 2008 and $15.5/kWh for a 350 bar tank which is a 9% reduction compared to 2008 costs.

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[27] Honda 2009

[28] U.S. DOE 2008b

Table 3: Hydrogen Tank and Performance Targets

(Dillich, 2009)

	2015 (new)	**2015 (old)**	**Ultimate Target**
System Gravimetric Density [wt. %] (kWh/kg)	[5.5] (1.8)	[9] (3.0)	[7.5] (2.5)
System Volumetric Density [g/L] (kWh/L)	[40] (1.3)	[81] (2.7)	[70] (2.3)
System Fill Time for 5-kg fill [min] (kgH_2/min)	[3.3] (1.5)	[2.5] (2.0)	[2.5] (2.0)
System Cost [\$/kgH_2] (\$kWh$_{net}$)	TBD	[67] (2)	TBD

3.5 Hydrogen Production

Hydrogen can be produced via multiple pathways. The U.S. DOE has evaluated and funded research for the most common routes such as steam reformation of natural gas, bio-derived renewable liquids and by splitting water (electrolysis).[9] To date, hydrogen produced from steam methane reformation (SMR) is the most cost effective pathway[29]. Currently, hydrogen produced from distributed natural gas is $2-3/gasoline gallon equivalent (gge).[29] The other two pathways have achieved significant efficiency increases but the $2-3/gge delivered hydrogen is not projected to be achieved until 2015-2020 timeframe (assume 1,500 kg/day and 500 units/year).

The California GREET Model describes the pathway for compressed gaseous hydrogen in terms of energy consumption and GHG emissions (pathway assumes North American natural gas feedstock). Table 4 indicates the relative contribution of each distinct component of this pathway. From an energy perspective, hydrogen production (16.5%), hydrogen liquefaction (31.9%) and hydrogen compression (10%) require the most energy in the hydrogen production pathway on a well to tank basis. In terms of CO_2 emissions hydrogen production (80.9%), hydrogen liquefaction (43.4%) and hydrogen compression (9.2%) contribute the largest to GHG emissions.[25] The modeled high-volume cost of gaseous hydrogen delivery via tube trailer is approximately $2.60/gge (terminal cost = $0.36, tube trailer = $0.76, station compression = $0.77, on-site storage = $0.48, and other station cost = $0.23) and the cost of liquid hydrogen delivery via tanker truck is approximately $3.32/gge (terminal cost = $1.83, liquid hydrogen truck = $0.28, on-site storage = $0.68, and other station cost = $0.53).[30]

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[29] U.S. DOE 2009c

[30] U.S. DOE 2009g. Standford, Joseph. "Modeled High-volume Cost of Major Hydrogen Production Pathways and Modeled High-volume Cost of Major Hydrogen Delivery Pathways". Received November, 12, 2009.

Table 4: Energy Contribution and GHG Emissions for Production of Compressed Hydrogen (CA GREET Model)

Percent Energy Contribution for Compressed Gaseous H_2		GHG Emissions Compressed Gaseous H_2 (gCO_2e/MJ)
Well to Tank (WTT)		
Feedstock	2.8%	8.2%
Hydrogen Production	16.5%	80.9%
Hydrogen Liquefaction	31.9%	43.4%
Distribution and Storage	0.4%	0.55%
Compression	10%	9.2%
Tank to Well (TTW)	**61.6**	**142.25**
Carbon/Energy in Fuel	38.4%	0%
Vehicle CH_4 and N_2O	0%	0%
Total Well to Wheel (WTW)	**100%**	**142.25**

3.6 Fuel Cell Vehicle Technology Status Conclusions

While many technical barriers such as cold start difficulties, limited range, long refueling time, low power density, high stack weight and large stack volume have been overcome, challenges remain. High cost and insufficient durability are the two biggest challenges according to U.S. DOE and industry stakeholders for fuel cell stacks to meet targets and for FCV commercialization. The U.S. DOE estimates the 2009 cost assessment of fuel cell systems to be \$61/kW, which is a 16% reduction in one year.[31] However, this cost still prevents FCVs from mass-market commercialization. The fuel cell system cost estimate includes the 80 kW_{net} direct hydrogen PEM fuel cell stack and balance of plant (BOP) at high production volumes (500,000 units per year). It is important to note that the U.S. DOE cost estimate excludes the hydrogen storage tank. The U.S. DOE 2015 fuel cell system target is \$30/kW and was set to drive down fuel cell system costs in order for fuel cell systems to be competitive with gasoline internal combustion engines. Accordingly, the U.S. DOE estimates that automotive engines cost between \$25-35/kW.[32] As a result, 2009 fuel cell system cost (at high volumes) is approximately two times the cost of an internal combustion engine.[32] All industry stakeholders agree that continued fuel cell R&D needs to occur in order to reach commercial viability. Most companies that are aggressively pursing FCVs believe the U.S. DOE targets are reasonable and several companies believe FCV commercialization can be achieved before U.S. DOE cost targets are reached.

Durability of the fuel cell system is improving and some reports indicate achieving U.S. DOE targets in laboratory testing. However, there has been little real-world validation of 2010 and 2015 durability targets. It is important to note that durability can be "bought"

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[31] U.S. DOE 2009e

[32] U.S. DOE 2009f. United States Department of Energy. Office of Energy Efficiency and Renewable Energy. "Hydrogen, Fuel Cells & Infrastructure Multi-Year Research, Development and Demonstration Plan". Updated April 2009.

by adding additional fuel cells but at extreme cost (and volume concessions). Several companies suggest that the next iteration of the ZEV regulation should allow for additional time before high numbers of ZEVs are required. These companies believe with more time they will be able to devote additional efforts to increasing fuel cell stack durability and to achieving cost reductions.

While infrastructure is not directly part of the FCV, it is a vital component of FCV commercialization success. At present, hydrogen-fueling infrastructure in California is inadequate and many automakers will base future commercialization plans on hydrogen fuel availability. Hydrogen fueling stations are expensive and require government support to build. It is essential that federal and state government show a strong signal of sustained support for FCVs by investing in R&D of FCVs as well as hydrogen infrastructure. ARB will continue to pursue hydrogen fueling infrastructure implementation through the Alternative and Renewable Fuel and Vehicle Technology Program (AB 118).

Given the high cost, low durability and lack of hydrogen fueling infrastructure, hydrogen FCVs are not commercially viable within this decade. However, many reports indicate that FCVs play a critical role in providing zero tailpipe emissions and GHG emission reductions in the passenger vehicle sub-sector and could be commercialized around 2015.

There is consensus in industry that continued investments should be made in the following areas:

- develop membranes for high temperature, low-relative humidity operation,
- increase catalyst activity and reduce platinum group metal loading to lower fuel cell cost,
- design strategies to reduce stack component degradation,
- optimize water management properties,
- reduce on-board hydrogen tank cost while increasing quantity of hydrogen stored,
- continued government support to fund hydrogen FCV R&D and hydrogen fueling infrastructure over the long-term.

4.0 Current Status of Battery Technology

In 2007, the Panel reported:

> "The prospects of PHEVs … were judged negatively by most major automobile manufacturers until recently. However, several manufacturers are now active in modeling, designing, and evaluating various PHEV architectures and technologies, with consequent attention to candidate battery technologies and their prospects."[33]

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[33] Kalhammer 2007. Kalhammer, Fritz R., et al. "Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Review Panel 2007".

Since 2007, PHEV development programs have expanded and are now underway at every large volume OEM. Automakers with the earliest development programs have further expanded those 2007 programs and have progressed to pre-production prototype evaluations. Additionally, staff believes that there are now BEV development programs at every intermediate[34] and large volume auto manufacturer. Although some of this activity is admittedly ARB ZEV regulation-driven, this is a remarkable shift in only 2 years.

4.1 Battery-based Energy Storage Systems and Vehicles

While past ARB reviews of vehicle energy storage technologies have covered a wide variety of battery chemistries, this review will focus only on an update of lithium ion (Li Ion) based energy storage technology. This narrow focus does not imply that alternatives to Li Ion batteries will not be implemented in commercial BEVs. Li Ion alternatives are still expected to be applied to commercial BEVs, but all large volume automakers[35] are currently planning to use Li Ion in their near-to-mid term PHEVs and BEVs for deployment in California. It should be noted that at least 2 of the recently announced American Recovery and Reinvestment Act (ARRA) grant awards were allocated to advanced lead acid batteries,[36]. It is still likely that lead acid, nickel-metal hydride (NiMH), sodium-based, and other batteries will continue to be developed for electric-drive vehicles. Still, the majority of near-term PHEV and BEV light-duty vehicles will make use of Li Ion technologies. This report will focus on near-to-mid term (2010-2020) Li Ion or Li Ion derivative batteries with sufficient capacity for application in PHEVs and BEVs (~5-95 kWhr)[37].

There has been a recent increase in both government and private research funding allocated to longer-term energy storage technologies based on alternative electrode couples (materials). These batteries would have significantly higher storage capability and lower $/kWhr cost than is achievable with Li Ion derivatives. With specific energy goals of more than 1,000 whr/kg, these long-term “super batteries” are the subject of extensive and increasingly well-funded world-wide research efforts. However, even if these “super batteries” began demonstrating feasibility in laboratory demonstrations, they would not be sufficiently proven for utilization in more demanding automotive applications for quite some time.

There are significant efforts underway to further develop Li Ion technology for the non-vehicle consumer market in the next several years, and some of these improvements may be applicable to automotive applications in 2015+. The primary focus of small consumer product Li Ion formulations is continued progress in increasing energy capacity, with 200 watt-hour per kilogram (whr/kg) cell level performance expected in the very near future. It remains to be seen whether these upcoming energy

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[34] Intermediate volume manufacturers produce between 4,500 and 60,000 vehicles per year in California, as defined in California Code of Regulations, Section 1900.

[35] A large volume manufacturer produces 60,000 vehicles per year in California, as defined in California Code of Regulations, Section 1900.

[36] These PbA-related ARRA awards include $34.3M to Exide (lead carbon electrodes), and $32.5M to East Penn Manufacturing (PbA-carbon supercapacitor combination).

[37] Smaller Li Ion battery systems for application in conventional HEVs are under development, but NiHM technology is expected to dominate in HEVs for many more years.

improvements will also result in reduced cost per unit energy ($/kWhr) or have applicability to automotive applications.

4.2 Near-term Battery Cost, Durability, & Performance Status (2010-2015)

The most significant challenges to widespread application of large Li Ion battery systems in vehicles still remain the same as the Panel's 2007 findings:

- High cost, particularly in transitional low-to-mid production volume applications in 2010-2015,
- Unknown durability in real-life, on-vehicle, variable-climate conditions, and
- Safety and abuse tolerance.

Several automakers reported that U.S. DOE/ and United States Advanced Battery Consortium (US ABC) battery performance and cost targets are no longer relevant and should be ignored, updated, or expressed in an alternative method that periodically adapts to external circumstances. US ABC performance and cost targets are based upon a fixed set of historical assumptions. However, these assumptions are dynamic values and should be periodically re-examined and targets revised in the same way that Federal fuel cell performance and cost targets are periodically revised.

There are a variety of Li Ion formulations under consideration for use in near-term automotive applications; in particular, there are several different cathode materials and material combinations. Selection of a particular formulation involves tradeoffs in specific energy, abuse tolerance, stability at elevated temperature, and other considerations. While iron phosphate ($LiFePO_4$) is frequently mentioned as a highly desirable future cathode material, the majority of Li Ion batteries destined for near-to-mid term automotive deployments will also include mixed oxide of nickel, cobalt, aluminum (NCA), mixed oxide of nickel, cobalt, and manganese (NCM), lithium manganese spinel (LMS), or combinations of these oxides. Proponents of $LiFePO_4$ claim that its lower specific energy performance is partially offset by its ability to operate over a wider SOC (state of charge) window, resulting in a higher "usable" whr/kg fraction than with other competing cathode materials. While cost differences in cathode materials are frequently cited as an important consideration in material selection, a recent TIAX cost modeling assessment of PHEV batteries[38] indicates that there may be:

> "…significant cost range overlap between the cathode classes (chemistries), with battery costs "bottoming" just below $300/ kWhr, and … wider variation within each chemistry than between chemistries".

While this TIAX modeling conclusion was directed at cost modeling for a 5.5 kWhr PHEV battery system and may not be applicable to larger 16+ kWhr capacity PHEVs or 24+ kWhr BEV systems, it does indicate that as long as safety requirements can be met, near-term cathode materials selection tradeoffs are more likely to be made on the basis of specific energy and durability considerations.

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[38] U.S. DOE 2009d. Barnett, Brian, et al. "PHEV Battery Cost Assessment". Annual Merit Review. TIAX LCC, May 19, 2009

During the 2007 review, the Panel reported that a cost range of $340- $420/kWh (@500 MWh/year production rate) and $240- $280/kWh (@2,500 MWh/year) were representative of manufacturers' specific cost projections for Li Ion modules[39]. When these results are combined with the Panel's module-to-system scaling factors, the Panel report system-level battery costs are summarized in Table 5 below.

Table 5: 2007 Expert Panel Long-Term Battery System Cost Summary

		500 MWhr/ year[40]		2,500 MWhr/ year	
Application	Scaling Factor (module-to-pack) [41]	Module Cost Range ($/ kWhr)	Pack Cost Range ($/ kWhr)	Module Cost Range ($/ kWhr)	Pack Cost Range ($/ kWhr)
Type II + BEV	1.2	340- 420	410-500	240-280	290-340
Type II BEV	1.25	340- 420	425-525	240-280	300-350
Type 1.5 BEV or ~40 mile PHEV (~16 kWhr)	1.33	340- 420	450-560	240-280	320-370
PHEV (~7 kWhr)	1.42	340- 420	480-600	240-280	340-400

TIAX LLC recently reported that the full range of PHEV battery manufacturing modeled in their recent study[42] resulted in cost projections ranging from $264/ kWhr to $710/ kWhr for 5.5 kWhr of usable power in cylindrical can format. Somewhat lower cost results would be expected if modeling battery systems suitable for PHEVs and BEVs in lower cost "pouch" formats and higher system energy capacities. The range of values from the Panel estimates ($340- $400 /kWhr) fall within the range of values from this TIAX study.

Tesla Motors manufactures their battery systems with laptop cells that are already made on high-volume production lines. These "18650" type cylindrical Li Ion cells are primarily designed for the laptop consumer industry and cost in the range of $200-$250/ kWhr.[43]. When these cells are integrated into laptop battery pack systems, costs range from $400-$700/ kWhr. The additional components and assembly needed

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[39] Using 45Ah high energy-design cells

[40] Production volume of 500 MWhr/ year is approximately equal to 20,000 Nissan Leaf EVs/ year (assuming 24-25 kWhr/ pack)

[41] P45 of ARB Independent Expert Panel 2007 Report (note: applies to higher amp hour cell sizes of the type expected for automotive-specific Li Ion cell designs, and not for 18650 cell application to automotive battery systems. This 18650 automotive scaling factor is believed to be much higher than the values shown above)

[42] U.S. DOE 2009d. Assumptions for this statistical, multi-variable sensitivity analysis included: cylindrical cell design, 10-90% SOC range cap in addition to a further capacity reduction "fade" variable, and all supplied materials were treated as outside-purchased and included supplier mark-ups

[43] AABC 2009a. Spotnitz, Dr. Robert. "Large Lithium-Ion Battery Design Principles". Tutorial A. Advanced Automotive Batteries Conference. June 8, 2009. Other sources indicate laptop (cell?) costs are higher- on the order of ~$300-$400/ kWhr.

[44] to build an 8-cell laptop battery pack is a higher fraction of cell cost than the expected 1.2-1.42X [45] cell-to-pack scaling factor for a PHEV, EREV, or BEV battery system constructed from much larger, high Ahr cells. If high-volume laptop cells were processed on a medium-volume pack assembly processing line at a near future Tesla Motors plant (scaling factor 1.6X, lower in future) then these systems would cost on the order of $320-$400 /kWhr. These assumptions would also seem to be validated by a current program at Tesla Motors where customers may pre-pay $12,000 now, and in return, receive a replacement battery pack after seven years. If a future value of $17,000 is assumed, this works out to a retail price of approximately $309/ kWhr, and if a manufacturer-to-customer markup of 1.2- 1.6X is also assumed, this may indicate that Tesla Motors anticipates their battery systems cost will drop below $260 / kWhr within 7 years.

While comparisons to laptop cell derived systems may give some indication of the lower cost limit in future automotive design battery costs, large risk-averse automakers may have more stringent requirements for long-life (more than 10 years versus 1 to 4 years in laptops, or perhaps 7 years in a Tesla) and superior cell-level abuse tolerance. Because of these differences, laptop battery costs may not be applicable to estimation of near-term automotive-specification battery system costs.

Regardless of Li Ion chemistry, industry is divided into two camps when it comes to choosing how to package Li Ion battery cells: Welded steel or aluminum can versus polymer flat package “pouches.” Both packaging types have their advantages and disadvantages:

Welded Can (steel or aluminum):
  (+) reliable sealing, high mechanical strength, may contain pressure
  (-) higher cost
  (-) harder to extract heat
  (-) heavier

Pouch Packaging Approach:
  (+) lower cost potential
  (+) simple headers, more current collector options
  (+) light weight
  (+) large aspect ratio for superior heat transfer
  (-) potential (or unknown) oxygen and water ingress rates
  (-) need to provide additional mechanical support
  (-) cannot contain pressure/ cell cannot be allowed to “balloon” (will rupture for safety, but no longer usable after rupture)

This can versus pouch packaging choice may have a very large impact on cost, but some industry experts still consider pouch construction to be of higher risk. However,

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[44] These additional battery system parts include packaging, cooling components, sensors, charge control electronic, safety systems, etc. The full system cost is sometimes estimated using “scaling factors” which vary by PHEV or BEV pack size, but are usually 1.2-1.4X cell cost (additional parts are 20-40 % of the cell costs).

[45] Kalhammer 2007.

two of the largest electric vehicle programs destined for near-term production incorporate pouch-construction cells (Nissan/ AESC: Leaf, and GM/ LG Chem: Volt).

Some automakers indicated that several battery cell suppliers, all free to compete, must reach volumes of greater than 100,000 systems per year to meet aggressive cost targets, and that an industry-wide standard for the large cell formats must be developed in order to help drive down costs. Others disagree or believe that it is premature to begin efforts to set any industry standards at this time. Advocates argue that a standard could incorporate a large degree of flexibility, for example, one that would lock a pouch cell size in 2 of its 3 dimensions. No cell standardization efforts are underway in the United States at this time.

The automotive market is proceeding with application of existing and "evolutionary" Li Ion technology that is becoming increasingly well characterized, while the consumer market may move forward more aggressively with significantly higher energy technologies as a result of more "revolutionary" changes.[46] If "Super" Li Ion batteries become available in the consumer market in 2010, they would not be implemented in automotive applications until 2015 or even later, which is beyond the scope of this technology review.

Staff believes that the range of potential costs reported by the Panel for existing Li Ion battery technology in high volume production has not changed since 2007 and remains valid ($290-$400 / kWhr, depending on application). The more immediate challenge is how to introduce and build a market for large automotive Li Ion battery systems before high production volumes provide greater economies of scale and lower battery cost.

While high production volume Li Ion battery system costs are expected to drop below $400 / kWhr sometime after 2015, and less than $300 / kWhr in future high production volumes they will, unfortunately, cost 2 to 3 times more in the next 5 years as PHEVs and BEVs are first introduced into the automotive market. Automakers reported widely varying costs during this introductory period, with some claiming current industry prices for small PHEV systems "around $800/ kWhr", and others as high as $1,000/ kWhr. Some automakers reported PHEV and BEV near-term, moderate volume costs would be on the order of $500-$600 /kWhr, with evolutionary changes and moderate volume production "next generation" design changes necessary before costs move further down into the $400-500/ kWhr range.[47] For comparison, current retail price (not OEM cost) for a Tesla Roadster replacement pack is $36,000 [48]. While Tesla has not revealed what their markup is on this system, it is reasonable to assume it is in the range of 1.2 to1.6 times. If true, this would mean that, in very low volume production (<100 MWhr/yr), Tesla Motors' present cost for a 55 kWhr battery system may be

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[46] For example, silicon-based anode materials may replace carbon, etc.

[47] Small PHEV systems cost much more on a per-kWhr basis due to differences in cell design and larger system integration costs relative to the batteries themselves (higher scaling factor).

[48] From Tesla Motors website, http://www.teslamotors.com/blog2/?p=70 "Customers may pay $12,000, €10,000 or £9,000 up front and in return receive a replacement battery pack after seven years. Customers will also have the option of replacing the pack earlier at a premium or later for a partial refund. With the low production volume of the Tesla Roadster, the current replacement price of the pack is almost three times that number."

somewhere in the range of $409 to $545/ kWhr. Staff believes that this is probably representative of where manufacturers will be within five years.

Large Li Ion Battery System Safety and Abuse Tolerance

In the past, safety was a key concern with automakers that were considering the application of Li Ion in vehicle applications. Considerable progress has been made in the recent years to the point where most automakers now believe that safety still requires care in design and engineering, but is now a manageable issue. In the near term, some have also chosen to limit cell size for safety considerations until further "intrinsic" safety features can be incorporated into cells. This is done because smaller cells contain less energy, and if critical limits are reached, there is less likelihood that a fire can propagate to adjacent cells in the battery system. Battery manufacturers are busy developing less reactive cathodes, improved electrolytes, and many are already incorporating new ceramic-coated separators to enhance safety. Improvements with heat transfer also yield higher safety margins by limiting peak temperatures during runaway conditions, and by reducing energy transferred to adjacent cells.[49]

Although further improvements at both cell and systems levels are sought after and expected in coming years, most automakers, battery suppliers, and industry experts are confident that near-term automotive systems are now safe enough for automotive deployments, with one key exception. Industry experts warn that non-OEM vehicles, so-called "conversion" PHEVs, are

> "actually the highest risk for the success of Lithium ion in automotive…The less of this (that) happens, the better for the industry longer term… It can be done, but it will take mature, responsible engineering with a long term view."[50]

The challenge is that there are presently no safety standards to sell Li Ion conversion vehicles to the public as there are, for example, with CNG conversions. OEMs are highly motivated to engineer safe automobiles because they must maintain a reputation for quality in the marketplace to ensure their own long-term survival. Small conversion companies usually cannot afford this investment in engineering expense and are not motivated by the same long-term considerations.

Large Li Ion Battery System Durability

Substantial progress continues to be made in the cycle life of Li Ion batteries: durability may eventually be calendar-life-limited in many electric vehicle applications. Cycle life limitations may be much more of a challenge for small PHEV systems than for BEVs. This is because cycle life is an exponential function of depth of discharge, and the larger capacity PHEV and BEV systems may not see full discharges on a frequent basis. This is one area where customer behavior, and in particular, workplace charging infrastructure availability may become a key issue.

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[49] One advantage of pouch packaging is that they have very large aspect ratios that enable good heat transfer

[50] AABC 2009b. Anderman, Dr. Menahem. "Value Proposition Analysis for Lithium-Ion Batteries in Automotive Applications". Tutorial E. Advanced Automotive Batteries Conference. June 8, 2009.

Most manufacturers agree that storage temperature is probably the most important factor when it comes to Li Ion battery system durability. The calendar life of most Li Ion batteries[51] is significantly degraded at elevated temperatures during the 90% of the time that PHEVs or BEVs are parked, and in particular, when batteries are at both high SOC and temperature. Accurate and reliable control of cell voltage and temperature are critical requirements for achieving long life and adequate safety of Li Ion batteries. While all automakers continue to engineer reliable systems to monitor and limit cell voltages, control of temperature is an area where their design solutions greatly diverge. Some are planning sealed batteries with no air or liquid cooling systems at all. Others consider the need to limit long-term elevated battery temperature critical enough to incorporate “active” systems to pump heat out of the battery, even when the vehicle is not being driven or actively charging. The remaining automakers are planning to make use of “passive” systems that divert sometimes-conditioned passenger cabin air into their battery systems for cooling; similar to the existing systems in most conventional NiMh-equipped HEVs. DOE funded researchers at NREL have been developing thermal analysis models to evaluate potential climate effects on battery life. Their preliminary results indicate that warmer climate conditions may have a significant negative impact on life; for example, an additional 15% battery power loss in 15 years for electric vehicles in Phoenix, AZ relative to other areas[52]. While active battery cooling systems add hardware cost and increase energy usage in warm climates, advocates of secondary use of batteries claim that these costs may be recouped by increasing a battery’s potential usefulness at vehicle end-of-life.

There are also severe challenges with cool climate application of PHEVs and BEVs, but automakers are now confident that the safety issues associated with attempting to charge in cold weather can be adequately addressed. Automakers are, however, universally in agreement that Li Ion battery systems, and in particular, BEVs, may not be functionally appropriate for all climates in the United States. While ARB is tasked with examining the suitability of technologies for automotive application in California, the conclusions reached might not be universally applicable to other states. If it were possible that BEV batteries could be heated and maintained at optimal temperatures in cold climates, this increased energy use would have to be considered when computing upstream CO_2e emissions and operating costs relative to BEVs in California.[53]

4.3 Large Li Ion Vehicle Application & Engineering Challenges

One of the challenges in applying many of the current Li Ion battery chemistries to PHEV and BEV applications is that they are likely to spend most of their lives at or near maximum SOC unless equipped with user-selectable end-of-charge SOC control features. For drivers who are not planning to drive again soon or to not drive very far (tomorrow), it does not make sense to charge their vehicles to maximum range capacity. Extended storage time at both maximum SOC and elevated temperatures will

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[51] AABC 2009a.

[52] AABC 2009c. Pesaran, Ahmad. “Impacts of 3C’s of Battery on PHEV Value Proposition”. Advanced Automotive Batteries Conference. NREL. June 8, 2009.

[53] The only highway-capable BEV currently for sale in California, the Tesla Roadster, is equipped with two key design features intended to extend battery life: (1) an active battery thermal control system, and (2) a user specified upper SOC control.

greatly reduce calendar life. Tesla Motors allows drivers to choose from four different charge/operation modes with different SOC targets at the end of the charge cycle:

Tesla Roadster Mode Setting	SOC at end of charge cycle
Standard (default setting)	80% of max. usable range
Storage	35-45% of max. usable range
Performance or Range mode	100% of max. usable range

More than one large automaker is also considering a similar user control feature for upper SOC limit in order to extend the lifetime of batteries. This might be particularly useful for BEVs used in predictable commuter applications with workplace charging.

Tesla Motors is already exploring the warranty contract challenges that large automakers will encounter as they begin to sell BEVs and PHEVs in the next five years. It is difficult to fully understand proposed business models where batteries (or vehicles with large batteries) are leased instead of owned. The long-term performance (and value) of a large Li Ion battery system on a vehicle will be greatly affected by driver choices and climate history. For example, the Tesla Roadster Energy Storage System (Battery) warranty does not cover damage caused by:

- Exposing an unplugged vehicle to ambient temperatures above 120℉ (50℃) for over 24 hours,
- Storing an unplugged vehicle in temperatures below -40℉ (-40℃) for over seven days, or
- Leaving your vehicle unplugged where it discharges the battery to at or near zero state of charge.

While it is true that the lifetime of the Lithium cobalt batteries currently used in the Tesla Roadster may be more susceptible to driver choices and climate conditions than other battery chemistries, the same temperature and SOC considerations will still apply, to some degree, to other Li Ion batteries about to be introduced to the automotive market.

It is likely that leased batteries (those owned by a second party) will not be subject to the same care as those owned by vehicle operators. Leased battery lifetimes cannot be assumed to be equivalent to self-owned batteries. One possible way to address this issue is to further restrict driver choices with leased batteries; for example, to limit their SOC swing to a smaller percent than with non-leased batteries. A self-owned Type II BEV is assumed to be able to achieve a 100 mile range when the driver desires it, but the same BEV that is leased and is software restricted to a “standard” mode with only 80 miles of maximum range, would no longer be certified as a Type II BEV. Alternatively, leased battery systems may be restricted to use of battery chemistries that are more tolerant of diverse driver treatment (abuse?), but these may compromise performance in other regards. Lease rates may also have to vary according to local climate. No matter how these issues are addressed, it would seem that the durability of leased batteries will not be as good as owned ones, that long-term costs of leased batteries will be higher than customer-owned batteries, and that leases for large batteries will be much more complex than sales.

One further challenge with battery or BEV leasing is the requirement of a performance warranty, even on very old systems. Unlike conventional vehicles, which maintain consistent performance for up to 250k miles, vehicle electrochemical system performance will deteriorate with age. Most issues with batteries that are sold are likely to occur sometime after the original warranty has expired. No matter how old the leased battery systems or leased BEV is, it will always require an agreement that clearly describes and guarantees a verifiable minimum battery performance level. Lease rates might also have to be decreased as performance deteriorates, even if the vehicle still meets a drivers commute requirements. PHEVs and BEVs will need to be equipped with a means to assess battery performance relative to when it was new, a state of health (SOH) indicator, in order for a leased battery business model to work. An on-road range test would provide inconsistent results and even if it could be carefully implemented, would be cost prohibitive[54].

On-Vehicle SOC and SOH Determination

Automakers and battery developers have made good progress in developing accurate, on-vehicle systems to determine the SOC of a battery. This is a very important parameter for drivers who need to know exactly how much further they can drive. On-vehicle determination of SOH[55], however, has proven to be a much more challenging task that was originally expected. While automakers had assumed that SOH systems would be ready in time for the 2010-2014 introductions of PHEVs and BEVs, the first vehicles will not yet be equipped with fully-proven SOH determination capability. On-vehicle SOH determination is necessary to address the need for a way to assess whether a battery has failed under warranty, but is also critically needed for lease applications (see above), to address the needs of those who may someday want to purchase used PHEVs and BEVs, for insurance companies to value used equipment, and for pre-screening of batteries under consideration for secondary use.

4.4 Large Li Ion Automotive Battery Production Status

The Panel found that large manufacturers of Li Ion batteries “do not appear to be pursuing development of Li Ion batteries for Full Performance BEVs or for PHEVs”. The Panel was much more specific about application in BEVs, stating that they “… found no major battery manufacturer interest in high energy Li Ion batteries for FPBEV[56] applications.”[57] This situation has changed considerably since 2007. Large battery manufacturers are now demonstrating strong interest in producing high energy Li Ion

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[54] Range test service visit for 100 mile BEV: Diagnosis, charging, testing, and re-charging: >=5? hours of technician time for a single evaluation (not fully counting charge time)

[55] SOH is usually expressed as a fraction of current battery maximum capacity divided by rated (or new) capacity

[56] FPBEV = “Full Performance Battery Electric Vehicle”. As late as 2007, it was uncertain whether automakers would be introducing commercial City EVs into the U.S. market that lacked sufficient performance capability for U.S. freeway driving. Since 2007, all EV products announced by major automakers have speed capability that greatly exceeds the (low performance) City EVs of the 1990s and will be “full performance”. The use of “full performance” terminology is no longer necessary except perhaps to distinguish these from NEVs, and the term “CityEV” is now more frequently applied to lower-range EV categories (50 – 75 mile).

[57] Kalhammer, 2007.

batteries for both PHEV and BEVs. This interest is most clearly expressed in the post 2007 announcements of joint ventures and purchase agreements between battery manufacturers and automakers / suppliers to produce automotive Li Ion batteries listed in Table 6 below.

Table 6: Publicly Announced Battery Manufacturer-Automaker/Supplier Joint Ventures

Automaker/ Suppliers	**Battery Manufacturer**	**Joint Venture**	**Publicly Announced**	**Vehicle Application**	**Plant Location(s)**
Toyota	Panasonic	Panasonic EV Energy	(1990s)	HEV + PHEV	
Nissan	NEC Corp.	Automotive Energy Supply Corporation (AESC)	3/09	HEV + BEV	Tokyo region (+ Tennessee?)
Honda	GS Yuasa	Blue Energy Co. Ltd.	4/09	HEV	Fukuchiyama, Kyoto
Volkswagen	Sanyo	(TBD)			
Mitsubishi	GS Yuasa	Lithium Energy Co. Ltd		BEV	Kusatsu
Coda Automotive	Yardney Technical Products	Coda Battery Systems LLC	6/09	BEV	
Bosch	Samsung SDI Co	SB LiMotive	8/09	BEV (BMW “Megacity”)	South Korea
Daimler AG	Evonik Industries AG	*Deutsche Accumotive GmbH & Co. KG*	7/08		*Kamenz, Saxony*
Hyundai Mobis Co.	LG Chem Ltd.			HEV and BEV (Hyundai and Kia)	
Ford	JCI/ SAFT	Not JV- Described as a “partnership”			

The most common arrangement in these joint ventures is for battery companies to put up approximately one-half the cost of the joint venture manufacturing facilities, which is a strong indicator of their confidence in future sales of Li Ion to the automobile industry. In addition to these joint ventures, some automakers plan to purchase cells directly from large battery manufacturers, fully engineer their own battery systems, and assemble these systems within automaker-owned facilities. U.S. DOE has announced awards totaling $1.5 billion for national manufacturing facilities to produce advanced automotive batteries. In addition to the DOE grants, the ARRA also included $8 billion in loans to Ford, Nissan, and Tesla under its Advanced Technology Vehicles Manufacturing Loan

Program. Nissan's $1.6 billion loan will be used to build manufacturing facilities for their Leaf BEV, and for plants to manufacture batteries for the Leaf. Tesla received $465 million to build production facilities for the upcoming Model S BEV, and for battery manufacturing equipment to support the Daimler Smart BEV.

Significant amounts of public funds and private capital are being invested in Li Ion battery production facilities, and most of this investment is for the manufacture of PHEV and BEV specific Li Ion batteries. This level of widespread pre-commercial progress has never been observed for a ZEV technology under review as part of the ARB's ZEV program. These investments are also the most significant indicator of Li Ion progress and acceptance in automotive applications since the 2007 technology assessment.

4.5 Battery Electric Vehicle Technology Status Conclusions

Large Li Ion battery development and production capacity buildup are proceeding at the pace necessary for the PHEV and BEV deployments required by the Board's ZEV Regulation through 2014. These batteries are now described as "pre-commercial" by most large automakers that are moving forward with PHEV and BEV deployments prior to 2014. While there has been extraordinary progress with electric vehicles, every automaker has cautioned ARB staff that there are extraordinary challenges to be overcome in order to sell and support large numbers of PHEVs and BEVs in California, and that these challenges will require considerable and coordinated efforts on the part of Federal, State, and local governments to make electric vehicles a reality. No automaker has stated that current design, or even next generation Li Ion batteries, will achieve sufficiently low cost to make them competitive with conventional vehicles without ongoing government incentives and/or tax credits. Several automakers do, however, believe that Li Ion battery systems will evolve sufficiently to allow automakers to sell cost competitive PHEVs and BEVs sometime prior to 2020, and that these electric-fueled vehicles will play a key role in automaker efforts to meet both corporate and California vehicle emissions reduction objectives.

5.0 2009 Survey Results

Survey Details
In June 2009, staff surveyed automotive companies, fuel cell suppliers and academic institutions to determine the latest in fuel cell technology and commercialization strategies. ARB staff carefully reviewed all surveys and has aggregated data in order to maintain business confidentiality while providing meaningful information. A total of 14 respondents provided extensive information on their organizations' environmental programs, GHG emission reduction strategies, current advanced technology vehicles, and planned advanced technology vehicles.

Manufacturer GHG Emission Reduction Goals
Automakers were asked to indicate the various types of ZEVs they plan to produce and to give a timeframe when advanced technology vehicles should begin commercialization in light of the GHG emission reduction goals. All automotive respondents described specific environmental programs aimed at reducing GHG

emissions and increasing efficiency in their light duty vehicle fleets. Many of the companies have done extensive GHG analyses in order to transform their vehicle fleet to meet California's AB 32 GHG reduction targets. The 2050 GHG emission reduction goals are a significant challenge for the passenger vehicle sub-sector and most companies are pursuing multiple advanced technology vehicles. While most stakeholders agree that increasing fuel efficiency in conventional ICE vehicles and reducing vehicle miles traveled (VMT) are important, they believe that conventional ICE efficiency increases alone will not come close to GHG emission reduction goals and VMT will be hard to reduce. Thus, a substantial effort must be placed on low-carbon fueled vehicles and low-carbon fuels. Companies have a variety of low-carbon fueled vehicles in their product strategies including BEVs (short-range), PHEVs, and FCVs.

Automakers believe GHG emission reductions required of the passenger vehicle sub-sector are massive and efforts must be made immediately to have any hope of achieving climate change reduction goals. Since the turnover rate in the passenger vehicle fleet typically requires multiple years, it is imperative that automakers begin early to commercialize advanced fuel vehicles.

In addition to placing low carbon fueled vehicles on the road, it is important to have a supply of low carbon fuels. All automakers agree that complementary infrastructure needs to be built in parallel with vehicle rollout. Many companies believe advanced vehicles should rollout by the middle of the next decade (~2015). In order to achieve the GHG emission levels, automakers believe a coordinated effort amongst all stakeholders in the transportation and energy supply sectors is vital. In 2009, the Board passed the Low Carbon Fuel Standard (LCFS) which requires a 10% reduction in carbon intensity of California's transportation fuels by 2020. Long term policies such as the LCFS will continue to require deep reductions in carbon from fuels, as manufacturers introduce ZEVs.

Vehicle Technologies

In the near term, all automotive manufacturers project that the conventional ICE will dominate the powertrain concepts for some time. A wide range of improvements will be made to increase fuel economy and decrease GHG emissions rather than focus on performance and increasing vehicle size. In the mid-term, conventional technologies will still dominate, however projections indicate an increase in market share of advanced technologies. In particular, electrification of passenger vehicles appear promising but depends on many variables including cost reduction, vehicle weight, and supporting infrastructure. Many companies are looking into PHEVs and short-range BEVs as mid-term solutions. In the long-term, short to mid-range BEVs, PHEVs with greater electric range and FCVs. Most companies are investing in multiple advanced vehicle technologies at the present time.

All automotive companies have a global market focus but recognize that there are significant differences in the various markets around the world. Automakers will place advanced vehicles in the countries based on many factors: regulatory climate (e.g. CO2e emission reduction regulations), government incentives, infrastructure deployment, consumer choice, local energy prices and cost effectiveness.

Survey responses suggested that automotive companies with strong FCV commercialization plans are optimistic and indicate they will be ready to commercialize the technology in 2015. Other companies with FCVs in their portfolios commonly cite 2025 as a commercialization launch year. Overall, respondents stated it was a huge challenge to indicate $/kW at current volumes or at large volumes (500,000 per year) due to the many uncertainties. Over half the survey respondents included FCVs in their projected product portfolios. Some have demonstration fleets on the road and have performed extensive real-world testing. Others have less aggressive demonstration FCV programs but are pursuing fuel cells at the R&D level. While most companies agree there are multiple challenges to fuel cell commercialization, all companies believe cost and durability are the two greatest challenges. Half of the companies with aggressive FCV plans agree that the U.S. DOE targets are possible based on historical progress and current projections of cost reductions and durability increases. Some companies that are seriously pursuing FCVs believe that volumes alone cannot reduce cost but that there are still technical advances that need to be achieved before commercialization.

The survey responses indicate small, short-range BEVs and PHEVs will likely appear on the market within the next few years. While some companies are enthusiastic about market penetration of BEVs, most manufacturers are anxious about market acceptance, flooding the market with BEVs and battery costs. Automakers appear to be making small, short-range BEVs (~100 miles/charge) in the near-term as the most cost-effective ZEV compliance option. These vehicles offer a great alternative to conventional ICE vehicles for urbanites and commuters (<100 mile range).

PHEVs offer considerable advantages to BEVs and are slated to emerge within the next 2 to 3 years. They offer significant GHG emissions reductions and unlimited range at a fraction of the cost of BEVs. In order to achieve deep GHG emission reductions, PHEVs will need to use sustainable biofuels and be charged consistently. However, it is estimated that other transportation sectors such as heavy duty, marine and aviation will consume a majority of the future biofuel supply. As a result, PHEVs will likely have a limited market share due to inadequate biofuel supply. Furthermore, it is extremely difficult to estimate emissions from PHEVs given the difficulty in estimating charge frequency. The batteries onboard are significantly lighter and less expensive and will likely result in PHEVs being readily accepted in the marketplace. As with BEVs, PHEVs have the same infrastructure challenge and need government financial commitment to build-out adequate charging stations. In spite of the challenges, it seems reasonable that PHEVS will come to market in the near-term due to lower incremental cost different compared to conventional ICE vehicles.

Technology Stratification

There are a number of market advantages and disadvantages of FCVs, PHEVs and BEVs, with each automaker having a slightly different perspective. However, there is a general consensus regarding the main advantages and disadvantages of each technology. Most companies believe FCVs offer excellent range, significant environmental benefits and similar driving experience compared to conventional gasoline vehicles. Still, FCV commercialization currently cost prohibitive and refueling infrastructure is inadequate. Like FCVs, BEVs offer considerable environmental advantages but are extremely expensive and durability is not well defined. PHEVs offer environmental gains over conventional ICE vehicles but have a cost premium and battery life is a major concern. Therefore, most automakers are pursing multiple technologies at this time.

Most automakers are taking a portfolio approach in their ZEV product planning because they believe there is no single technology that will meet the 2050 goal. This multiple technology approach ensures that R&D continues on all technologies to reduce cost and increase durability.

Most also believe that these technologies will be applied non-uniformly across their product lines, and will vary according to a combination of vehicle size, duty cycle[58], application, local climate, and price range. Some believe that BEVs may even be the dominant technology in a new class of 2-seat mini-compact size vehicles, with BEV applications also extending throughout compact-size up to mid-size vehicles in urban and regional applications. PHEVs are expected to overlap with BEVs in the small-to-mid size range, and dominate in mid-size mixed applications and where longer distance travel is required. Fuel cell technology will be applied to mid-to-large vehicles with continuous or high-load applications and where range or refueling time restrictions cannot be accommodated. Lower range BEVs will be well-suited for commute, shared-car, and fleet-specific applications. Automaker product plans now include BEVs in ARB's lowest-range ZEV Regulation categories: Type I 50 mile and Type I.5 75 mile range BEVs.

Most automakers believe that the size of conventional vehicles they sell in the U.S., and in particular, the California market, will be getting significantly smaller. This downshift in size is due to a variety of contributing factors. However, if this downward trend is considered in conjunction with the suitability of BEVs and PHEVs in small-to-mid size classes, the end result of this fleet-wide size reduction could be an increase in the potential market share of BEVs and PHEVs.

FCVs offer major environmental benefits compared to the conventional ICE vehicle and some companies have publicly announced FCV commercialization in the 2015 timeframe. All automakers developing FCVs are aggressively working to address cost and durability issues. Several automakers believe cost can be reduced sufficiently for FCVs to enter the market by 2015 if hydrogen infrastructure is adequate. Automakers believe that consistent government funding of vehicle R&D and infrastructure is essential to reach commercial launch. While FCVs are needed to reduce GHG emissions, there is no single advanced technology that will achieve 80% GHG emission reductions alone. Therefore, it is necessary that all ZEVs succeed and a play a role in sustainable transportation. Top automaker's of FCV technology – Daimler, Ford, General Motors, Honda, Hyundai, Kia, Toyota and alliance Renault SA and Nissan issued a joint letter of understanding in September 2009 regarding development and commercialization of FCVs. The auto manufacturers strongly anticipate that from 2015

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[58] In this regard, "duty cycle" is meant to describe power VS time requirements, for example, continuous highway VS stop-and-go urban driving.

onwards, a significant number –"a few hundred thousand units over the initial products' lifecycles-of FCVs could be commercialized".[59]

Consumer Demand and Additional Policies
All organizations surveyed strongly support government incentives at the local, state and federal level to bring advanced technology vehicles to market. Furthermore, they believe government support and other complementary policies (e.g. infrastructure investment, incremental cost buy-down incentives, etc.) are required for a long-term GHG emission reduction strategy to be effective. To date, automotive manufacturers have fronted most of the investment in advanced technology vehicles with little-to-no investment required of energy providers and no cost passed to the consumer. Most automakers are radically shifting their production plans to make advance technology vehicles and will need all stakeholders to invest and share the risk in the sustainable transportation future.

All automotive manufacturers support a political climate that remains technology neutral with consistent financial support. Without consistent government support it will be near impossible to achieve GHG emission reduction goals in the passenger vehicle sub-sector. While early adopters will bear the incremental cost burden between conventional vehicles and advanced technology vehicles, the majority of consumers will not be inclined to purchase these vehicles due to the significant cost differential. Some companies suggest government funding should be sufficient to have initial incremental cost paid back by fuel savings over a 3-year period and these incentives should be phased out as volumes grow. Auto manufacturers recommend that government incentives for ZEVs should include:

- federal and state vehicle incentives for R&D,
- allow ZEVs to be exempt from motor vehicle tax, sales tax and vehicle registration fees,
- provide purchase incentives for consumers at point-of-sale (to buy-down upfront incremental price),
- fund ZEV infrastructure (home, workplace and public),
- offer HOV lane access, free parking, preferential parking in public spaces,
- give higher credit in ZEV program and GHG gas regulation program,
- offer free charging, toll road exemptions,
- grant incentives to offset fleet purchases or require a percentage of new fleet purchases be advanced technology vehicles,
- continue to develop Low Carbon Fuel Standard and Cap and Trade policies,
- require utilities to offer free home inspections for off-peak charging, and
- create or reform building codes to facilitate home/public refueling.[20]

Most automakers now have specific environmental strategies for their passenger vehicle product line in order to achieve California's GHG emission reduction goals.

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[59] OEM LOU 2009. OEM Letter of Understanding on the Development and Market Introduction of Fuel Cell Vehicles. Dated September 8, 2009.

While each company has a unique approach, most are converging on electrification of the passenger car through various advanced vehicle technologies. A majority of automakers have produced a few ZEV demonstration vehicles or have made public announcements of planned ZEV test fleets. All advanced technology vehicles will come at a significant cost premium and automakers strongly agree that the investment in sustainable transportation should be shared amongst all stakeholders including the consumer.

6.0 Conclusion

Governments around the world are increasingly concerned about energy security, fluctuating petroleum prices, and reducing smog and GHG emissions. Since the passenger vehicle sub-sector contributes to a large portion of smog forming and GHG emissions, it is essential to increase vehicle efficiency and reduce smog and GHG emissions from passenger cars.[3]

Most auto manufacturers have publically announced plans to deploy ZEVs to decrease criteria pollutants and GHG emissions from their light duty vehicles. All survey respondents have indicated specific sustainable program plans aimed at greening their vehicles. The 2050 GHG emission reduction goals are a huge challenge for the passenger vehicle sub-sector and all automakers believe there is no single advanced technology vehicle that will enable the deep reductions that must occur and therefore are pursing multiple advanced technology vehicles.

Rather than some technologies “winning” over others, manufacturers agree that FCVs, PHEVs and BEVs all have unique market opportunities within sustainable transportation. For example, small, short-range BEVs could be used for intercity travel and daily commutes, PHEVs could be medium sized cars and used for intra-city travel, FCVs could be medium-to-large sized vehicles and used for long distance travel.

In the near-term, it is likely that conventional vehicles will continue to make efficiency gains and make up most of new vehicle sales. Therefore, it is essential that all technical advances be directed toward decreasing fuel consumption rather than compensate for increased performance and weight. In addition to conventional ICE vehicles, HEV technology is a promising pathway to cost-effective reduction in fuel use.[2] Within the next several years, automaker’s will likely produce small, more efficient conventional ICE vehicles as a cheaper approach to GHG reductions and slowly hybridize their vehicle portfolios.

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APPENDIX A

CONFIDENTIAL ZERO EMISSION VEHICLE TECHNOLOGY STATUS SURVEY

JUNE 25, 2009

California Air Resources Board
Sustainable Transportation Technology Branch
Zero Emission Vehicle Implementation Section

OVERVIEW

The California Air Resources Board (ARB or the Board) is conducting a confidential survey to augment stakeholder discussions and ARB staff research for the Zero Emission Vehicle (ZEV) 2.0 Technical Support Document (TSD). This survey will be used, along with publicly available reports, data and analyses, to assess the prospects of ZEV technology commercialization. The survey is intended to:

- capture information regarding ZEV technology status: cost, current state of technology, future production plans, timelines, key technical issues/barriers, and commercialization timeframe, and
- be one source, among several, in ARB's development of the TSD.

ARB acknowledges each type of ZEV is in a different state of commercial readiness, with varying market entry barriers. ARB also acknowledges that the survey questions request information that may be sensitive in a competitive aspect. However, accurate information is critical for staff's ability to realistically assess the status of each ZEV technology prior to ZEV regulation revisions.

ARB staff requests documentation, data and written answers be submitted in response to this survey. A phone or in-person meeting with staff may also be requested to further discuss your organization's answers to survey questions.

CONFIDENTIALITY

ARB protects survey documentation, data records, written responses, and other records designated as confidential business information or trade secret from disclosure to extent permitted by state law and ARB regulations. Please clearly mark survey materials or portions of materials as "business confidential" to indicate those materials that ARB staff is asked to protect from disclosure consistent with state law and ARB regulations.

TIMELINE

June 22, 2009 – August 31, 2009	Teleconferences, in-person meetings with manufacturers and other stakeholders
August 31, 2009	Survey response deadline
Tuesday, September 8, 2009	Draft TSD release date
Tuesday, November, 10, 2009	TSD release date
Thursday, December, 10, 2009	Informational item presented at December Board Meeting

Acronyms

- AER…………………………………………………………..All-Electric Range
- AT-PZEV…………… Advanced Technology Partial Zero Emission Vehicle
- BEV…………………………………………………..Battery Electric Vehicle
- CNG…………………………………………….....Compressed Natural Gas
- EAER……………………………………….…Equivalent All-Electric Range
- Enhanced AT-PZEV.......................Enhanced Advanced Technology PZEV
- FCEV………………………………………………Fuel Cell Electric Vehicle
- GHG………………………………………………………Greenhouse Gases
- HEV…………………………………………………...Hybrid Electric Vehicle
- HICE…………………………Hydrogen Internal Combustion Engine Vehicle
- HOV………………………………………………...High Occupancy Vehicle
- ICE…………………………………………….....Internal Combustion Engine
- kW……………………………………………………………………Kilowatt
- kWh………………………………………………………………Kilowatt-hour
- LDV……………………………………………………….....Light Duty Vehicle
- Li-Ion…………………………………………………………….Lithium Ion
- NEV…………………………………………Neighborhood Electric Vehicle
- OEM……………………………………...Original Equipment Manufacturer
- R_{cda}…………………………………………Actual Charge Depleting Range
- SULEV…………………………………..Super Ultra Low Emission Vehicle
- PHEV………………………………………....Plug-in Hybrid Electric Vehicle
- PZEV……………………………………………Partial Zero Emission Vehicle
- TSD……………………………………………Technical Support Document
- UDDS………………………………Urban Dynamometer Driving Schedule
- USABC………………………United States Advanced Battery Consortium
- USDOE……………………………...United States Department of Energy
- ZEV……………………………………………………Zero Emission Vehicle

Definitions

- Actual Charge Depleting Range or R_{cda} means the actual distance achieved by a hybrid electric vehicle on a specified driving cycle at the point when the zero emission energy storage device is depleted of off vehicle charge and regenerative braking derived energy.

- All-Electric Range means the total miles driven electrically (with engine off) before the engine turns on for the first time, after the battery has been fully charged. For a blended plug-in hybrid electric vehicle, the equivalent all electric range shall be considered the "all-electric range" of the vehicle.

- Advanced Technology Partial Zero Emission Vehicle means any partial zero emission vehicle with an allowance greater than 0.2 before application of the partial zero emission vehicle early introduction phase-in multiplier. Examples: hybrid electric vehicle or compressed natural gas-fueled vehicle meeting super ultra low emission vehicle emission standard.

- Battery Electric Vehicle means any vehicle that operates solely by use of a battery or battery pack, or that is powered primarily through use of electric battery or battery pack but uses a flywheel or capacitor that stores energy produced by the electric motor or through regenerative braking to assist in vehicle operation.

- Blended Plug-In Hybrid Electric Vehicle means a vehicle using both internal combustion engine and off-vehicle charge energy during the charge depleting mode of operation.

- Equivalent All-Electric Range means the portion of the total charge depleting range attributable to the use of electricity from the battery over a charge depleting range test.

- Enhanced Advanced Technology Partial Zero Emission Vehicle means any partial zero emission vehicle that has an allowance of 1.0 or greater per vehicle without multipliers and makes use of a zero emission vehicle fuel. Examples: plug-in hybrid vehicle or hydrogen internal combustion engine meeting super ultra low emission vehicle emission standard and applicable partial zero emission vehicle requirements.

- Global Fleet Size means the number of zero emission vehicles placed worldwide.

- Global Demonstration means 100's of vehicles placed worldwide.

- Global Pre-Commercialization means 1,000’s of vehicles placed worldwide.

- Global Early Commercialization means 10,000’s of vehicles placed worldwide.

- Global Full Commercialization means 100,000’s of vehicles per year placed worldwide.

- Neighborhood Electric Vehicle means any motor vehicle that meets the definition of Low-Speed Vehicle in section 385.5 of the Vehicle Code or in 49 CFR 571.500 (as it existed on July 1, 2000), and is certified to zero emission vehicle standards.

- Non Blended Plug-In Hybrid Electric Vehicle means a vehicle that uses off-vehicle charge energy exclusively for motive power during the charge depleting mode of operation.

- Plug-in Hybrid Electric Vehicle means a vehicle using motive power supplied by an internal combustion engine and off-vehicle electricity stored in batteries or other energy storage systems.

- Partial Zero Emission Vehicle means any vehicle that is delivered for sale in California and that qualifies for a partial zero emission vehicle allowance of at least 0.2. Among other requirements, a partial zero emission vehicle meets the super ultra low emission standard tailpipe standard, zero evaporative emission standard, and provides an extended emissions warranty of 15 years/150,000 miles.

- Urban Dynamometer Driving Schedule means a United States Environmental Protection Agency dynamometer test for light duty vehicles that represents city driving conditions as set forth in Appendix I 40 Code of Federal Regulations Part 86.

- Zero Emission Vehicle means any vehicle certified to zero emission standards, producing zero exhaust emissions of any criteria pollutant (or precursor pollutant) under any and all possible operational modes and conditions.

- ZEV Fuel means any fuel that provides traction energy in on-road zero emission vehicles. Examples: electricity, hydrogen, and compressed air.

Automotive Manufacturer Questionnaire

This automotive manufacturer questionnaire is intended to assist ARB staff in assessing the technical status of your organization's zero emission vehicle (ZEV) program, especially with regard to technology development, performance, timing of commercialization, and costs. The questionnaire pertains to general questions regarding projected ZEV technology commercialization, technology and vehicle technical information, and volume and cost challenges for ZEVs.

Wherever possible, reference your technical answers to the United States Department of Energy (US DOE) and United States Advanced Battery Consortium (US ABC) technical goals (attachments 1 and 2). This will improve our ability to assess all survey responses on a consistent level.

Not all questions are applicable to each company or organization. Please respond to the questions appropriate to your development and/or commercialization program. Any additional comments and suggestions not covered by the technical questionnaire are welcomed.

QUESTIONS:

1. To meet California's 2050 greenhouse gas (GHG) emission reduction goals (Executive Order S-03-05), the light duty vehicle (LDV) segment will likely need to reduce emissions by 80% below 1990 levels.

    a. What is your organization's vision for the types of vehicles such as zero emission vehicles and plug-in hybrid electric vehicles that would be commercialized in response to this goal?

    b. When do you envision advanced technology vehicle markets needing to evolve in order to achieve these 2050 goals?

    c. More specifically, what are your organization's advanced vehicle technology portfolio plans through 2020 (the next 10 years) as related to GHG emissions?

2. What are your organizations plans for advanced vehicle deployment in general regions around the world (e.g. United States, Europe, and Japan)? What are the motivating factors that drive those choices?

3. What are the market advantages and disadvantages of each technology listed below (e.g. vehicle purchase cost, operating cost, fueling convenience, perceived infrastructure access, "green" aspect of vehicle, etc.)?

    - Fuel Cell Electric Vehicle
    - Battery Electric Vehicles

- Plug-in Hybrid Electric Vehicles
- Hybrid Electric Vehicles
- Conventional Vehicles
- Alternative Fuel Vehicles (compressed natural gas, biodiesel, etc.)

4. What is the status of your organization's current and future ZEV programs under development? Please fill out a vehicle specification sheet (Attachment 3) for each vehicle your organization produces or intends to produce.

5. What challenges remain to meeting USDOE cost and performance goals and how do you foresee addressing them? Please refer to Attachment 1. If you do not feel the USDOE targets are appropriate, describe why the targets are not appropriate.

6. What will the cost per vehicle be at the following levels and what are the remaining challenges? Please use in the following tables as guides.

FUEL CELL VEHICLES

	When will production volumes reach the following levels (model year)?	Vehicle Cost ($)	Operating Cost ($)	Technical/Performance Issues	Other Commercialization Issues (infrastructure, codes and standards, etc.)
100's of vehicles					
1,000's of vehicles					
10,000's of vehicles					
100,000's of vehicles					

BATTERY ELECTRIC VEHICLES

	When will production volumes reach the following levels (model year)?	Vehicle Cost ($)	Operating Cost ($)	Technical/Performance Issues	Other Commercialization Issues (infrastructure, codes and standards, etc.)
100's of vehicles					
1,000's of vehicles					
10,000's of vehicles					
100,000's of vehicles					

PLUG-IN HYBRID VEHICLES

	When will production volumes reach the following levels (model year)?	Vehicle Cost ($)	Operating Cost ($)	Technical/Performance Issues	Other Commercialization Issues (infrastructure, codes and standards, etc.)
100's of vehicles					
1,000's of vehicles					
10,000's of vehicles					
100,000's of vehicles					

7. Does your organization recommend federal purchase incentives to support early market sales of ZEVs? If so, what level of funding is appropriate? What are other complementary policies that could aid in early market sales (e.g. HOV lane access)?

Fuel Cell Manufacturer Questionnaire

This fuel cell manufacturer questionnaire is intended to assist ARB staff in assessing the technical status of fuel cell systems, especially with regard to technology development, performance, timing of commercialization, and costs. The questionnaire pertains to fuel cell technology currently in development, technical goals for automotive fuel cell systems, technical issues impeding introduction of automotive fuel cell systems, and commercialization challenges.

Wherever possible, reference your technical answers to the US DOE technical targets (Attachment 1). This will improve our ability to assess all survey responses on a consistent level.

Not all questions are applicable to each company or organization. Please respond to the questions appropriate to your development and/or commercialization program. Any comments and suggestions not covered by the technical questionnaire are welcomed.

QUESTIONS:

1. Is your organization a vehicle system integrator (original equipment manufacturer), direct system component supplier (Tier 1) or second/third tier supplier (Tier II, III)?

2. Is the fuel cell application for primary propulsion power, traction power, auxiliary power or other?

3. What is the fuel cell type (e.g. proton exchange membrane, solid oxide fuel cell) and general performance characteristics of your system? Please provide your answers relative to the USDOE fuel cell technical targets in Attachment 1.

4. What are the first and subsequent automotive applications, e.g. cars, sport utility vehicle, trucks and/or buses?

5. Do you anticipate non-automotive applications for your fuel cell technology?

6. Please review the US DOE fuel cell system targets outlined in Attachment 1, and state your systems performance relative to these targets.

7. Which of the following performance topics still require research and development before commercialization? Please rank your answers in order of the difficulty of finding a solution.
    - Energy efficiency at part load and rated power
    - Fuel consumption on standard driving cycles (e.g. urban dynamometer

driving schedule)

- Durability
- Balance of plant requirements, e.g. thermal management, humidification, air and fuel
- Start up, shut down and storage issues
- Extreme environmental hot and cold ambient conditions
- Cold start time
- On-board hydrogen storage and purity requirements
- Noise, harshness and vibration
- Others?

8. Does your organization have plans to commercialize your automotive fuel cell technology? If so, in what volume and timeframe?

9. What are the challenges associated with developing and building an adequate OEM supplier base for the fuel cell industry? Characterize your answer in terms of what is needed to support varying production volumes (e.g. 1,000 vs. 10,000 vs. 100,000 vehicles).

Battery Manufacturer Questionnaire

This battery manufacturer questionnaire is intended to assist ARB staff in assessing the technical status of batteries, especially with regard to technology development, performance, timing of commercialization, and costs. The questionnaire pertains to: battery technology currently in development, technical goals for automotive batteries,technical issues impeding introduction, and commercialization challenges for automotive batteries.

Wherever possible, reference your technical answers to the US ABC technical targets (Attachment 2). This will improve our ability to assess all survey responses on a consistent level.

Note: Please provide separate answers in each question for battery technologies used in BEVs or PHEVs.

Not all questions are applicable to each company or organization. Please respond to the questions appropriate to your development and/or commercialization program. Any comments and suggestions not covered by the technical questionnaire are welcomed.

QUESTIONS:

1. What kind of battery chemistry is your organization developing? Please provide details of each battery chemistry.

2. Is your organization developing and/or marketing battery technologies in cell sizes suitable for BEVs (for example 40-100 Ah) and for PHEVs (15-50 Ah)? If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale])?

3. What are the technical problems that still need to be overcome to achieve commercial production of the technology (e.g. performance, cycle life, calendar life, safety issues, cost)?

4. What are the most prevalent non-technical barriers to commercial production?

5. Please review the US ABC battery system targets outlined in Attachment 2, and state your systems performance relative to these targets.

6. What is the cost of your organization's battery technology for BEV applications:
   (cell size 30-100 Ah, capacity 20-40 kWh) and PHEV applications
   (cell size 15-50 Ah, capacity 5-20 kWh).

Please provide separate answers if you produce both types of vehicles.

- Capacity, voltage and estimate cost of modules
    - at maximum current production rate (please indicate rate)
    - at 3,000 kWh per year
    - at 30,000 kWh per year
    - at 300,000 kWh per year

- Cost of balance of battery system (battery management system, case/tray, wiring, other hardware)
    - at maximum current production rate (please indicate rate)
    - at 3,000 kWh per year
    - at 30,000 kWh per year
    - at 300,000 kWh per year

7. Which technology advances are most likely to reduce battery cost? When does your organization expect these cost reductions to become part of commercially available technology?

8. Which technology advances are most likely to increase battery safety? When does your organization expect these safety increases to become part of commercially available technology?

Government, Academia, and Other Questionnaire

This questionnaire is intended to assist ARB in assessing the technical status of zero emission vehicle (ZEV) technologies, especially with regard to technology development, performance, timing of commercialization, and costs. The questionnaire pertains to your organization's perspectives on ZEV and ZEV enabling technology commercialization trends, and well as your organization's assessment of the current ZEV market. ARB sent specific surveys to original equipment manufacturers (OEM), battery manufacturers, and fuel cell manufacturers worldwide. This survey is being distributed to non-industry stakeholders, academia, and federal government agencies to gauge general trends of the status of ZEV technology and commercialization.

Not all questions are applicable to each company or organization. Please respond to the questions appropriate to your company or organization. Any comments and suggestions not covered by the technical questionnaire are welcomed.

1. To meet California's 2050 greenhouse gas (GHG) emission reduction goals (Executive Order S-03-05), the light duty vehicle (LDV) segment will likely need to reduce emissions by 80% below 1990 levels.
    a. What is your organization's vision for commercialization of the types of vehicles needed to meet California's 2050 goals, such as zero emission vehicles and plug-in hybrid electric vehicles?
    b. When do you envision advanced vehicle markets needing to evolve in order to achieve these 2050 goals?
    c. More specifically, what are your organization's thoughts on advanced vehicle technology portfolio plans needed by 2020 (the next 10 years) as it relates to GHG emissions and fuel economy?

2. What are the market advantages and disadvantages of each type of vehicles compared to the following vehicles? (e.g. vehicle purchase cost, operating cost, fueling convenience, perceived infrastructure access, "green" aspect of the vehicle, etc.)

    a. Fuel Cell Electric Vehicles
    b. Battery Electric Vehicles
    c. Plug-in Hybrid Electric Vehicles
    d. Hybrids Vehicles
    e. Conventional Vehicles
    f. Alternative Fuel Vehicles (Compressed Natural Gas, Biodiesel, etc.)

3. Please evaluate the US DOE Hydrogen Fuel Cell Vehicle Goals and the US ABC Goals (see Attachment 1 and 2). Explain any discrepancies your organization may have with goals listed, and provide additional goals your organization feels are necessary for successful ZEV and PHEV commercialization.

4. Does your organization recommend federal purchase incentives to support early market sales of ZEVs? If so, what level of funding is appropriate? What are other complementary policies that could aid in early market sales (e.g. HOV lane access, fueling infrastructure incentives, etc.)?

5. What are the challenges associated with developing and building an adequate OEM supplier base for the fuel cell or battery industry? Characterize your answer in terms of what is needed to support varying production volumes (e.g. 1,000 vs. 10,000 vs. 100,000 vehicles).

6. What are the technical problems that still need to be overcome to achieve commercial production of fuel cells (examples: performance, starts, calendar life, safety issues, cost)?
    a. Which technology advances are most likely to reduce battery cost?

    b. Which technology advances are most likely to increase battery safety?

7. What are the technical problems that still need to be overcome to achieve commercial production of batteries (examples: performance, cycle life, calendar life, safety issues, cost)?

8. What are the most prevalent non-technical barriers to commercial production of fuel cells and fuel cell vehicles?

9. What are the most prevalent non-technical barriers to commercial production of battery and battery electric vehicles?

Companies or Organizations Receiving Survey

Automobile Manufacturers
- BMW
- Chrysler
- Coda
- Daimler
- Fisker
- Ford
- General Motors
- Honda
- Hyundai
- Jaguar
- Kia
- Mazda
- Mitsubishi Motors
- Nissan
- Subaru
- Tesla
- Toyota
- Volkswagen
- Volvo

Battery Manufacturers
- A123 Battery
- Automotive Energy Supply Corporation (AESC)
- Altairnano
- BYD
- Compact Power
- Electrovaya
- Enerdel
- GAIA Akkumulatorenwerke
- GS/Yuasa
- Johnson Controls-Saft
- Kokam America
- Lithium Energy Japan
- Panasonic EV Energy (PEVE)
- Sanyo
- SK Energy

Fuel Cell Manufacturers
- ATCC
- Hydrogenics
- UTC Power

Government, Academia and Other

- Argonne National Laboratory
- Electric Power Research Institute (EPRI)
- Massachusetts Institute of Technology
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- United States Department of Energy
- University of California Davis (UC Davis)
- University of California, Irvine (UC Irvine)

Survey References

The following reference list is a summary of the information ARB will review to support the development of the ZEV Regulation revisions. This information will support various tasks, including the TSD, the greenhouse gas scenario analysis, and the infrastructure assessment that will inform the potential need for complementary policies.

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Survey Addendum

CONFIDENTIAL ZERO EMISSION VEHICLE TECHNOLOGY STATUS SURVEY

Addendum Release Date: July 29, 2009
Survey Release Date: June 25, 2009

Survey Clarifications

P. 5 - Definitions

The following definitions have been modified: (italics indicate additions)

- Global fleet size means the number of zero emission vehicles placed *by a single manufacturer in a single model year* worldwide
- Global demonstration means 100's of vehicles placed *by a single manufacturer in a single model year* worldwide
- Global pre-commercialization means 1000's of vehicles placed *by a single manufacturer in a single model year* worldwide
- Global early commercialization means 10,000's of vehicles placed *by a single manufacturer in a single model year* worldwide
- Global full commercialization means 100,000's of vehicles placed *by a single manufacturer in a single model year* worldwide

P. 7 – Automotive Manufacturer Questionnaire

The following are clarifications regarding questions 1a., 1b., and 1c.:

1a. What is your organization's vision for the types of vehicles such as zero emission vehicles and plug-in hybrid electric vehicles that would be commercialized in response to this goals?

This question is meant to be manufacturer specific, i.e. which type of vehicles each manufacturer plans to produce in order to meet California's long term greenhouse gas reduction goals.

1b. When do you envision advanced technology vehicle markets needing to evolve in order to achieve these 2050 goals?

This is an industry trend question, asking what the market sales & fleet penetration trends are for various advanced technology vehicles. Specifically, ARB Staff are looking for the following trends in the California market (global trends are also valuable if CA specifics can't be provided):

- *Market launch dates.*
- *Speed of technology introduction*

- *Ultimate market limits once fully commercialized for many years (i.e. are certain technologies limited by resource supply or customer expectations?)*

1c. More specifically, what are your organization's advanced vehicle technology portfolio plan through 2020 (the next 10 years) as related to GHG emissions?

This question is asking for each specific manufacturer's advanced vehicle technology portfolio, meaning conventional hybrids, plug-in hybrids, and zero emission vehicles.

P. 8,9 – Automotive Manufacturer Questionnaire

The following are definitions for questions asked in the tables regarding fuel cell vehicles, battery electric vehicles, and plug-in hybrid vehicles:

- *Vehicle cost means the manufacturing cost of the vehicle. Please supply research and development costs separately, if applicable.*
- ~~*Operating cost*~~ *(does not need to be answered)*
- *100's of vehicles per manufacturer, per model year, globally*
- *1,000's of vehicles per manufacturer, per model year, globally*
- *10,000's of vehicles per manufacturer, per model year, globally*
- *100,000's of vehicles per manufacturer, per model year, globally*

P. 12 – Battery Manufacturer Questionnaire

The following are clarifications regarding questions 1 and 6:

1. What kind of battery chemistry is your organization developing? Please provide details of each battery chemistry.

   Please be as specific as possible. Staff intends to use the answers provided to show general trends in battery chemistry for specific applications, i.e. "it appears that manufacturers will continue to use NiMH battery technology for conventional hybrids" or some similar conclusion that will be able to be drawn from the answers to this questions. It is not staff's intent to have a discussion about which specific lithium battery material combination is best suited for battery electric vehicles.

6. What is the cost of your organization's battery technology for BEV applications: (cell size 30-100 Ah, capacity 20-40kWh) and PHEV applications: (cell size 15-50 Ah, capacity 5-20 kWh)?

Cost in this question refers to the cost to the vehicle manufacturer of the battery system, as apposed to the cell cost.

APPENDIX B

U.S. Department of Energy Automotive Fuel Cell Targets

Technical targets for automotive applications: 80 kWe (net) integrated transportation fuel cell power systems operating on direct hydrogen.

Characteristic	Units	2010	2015
Energy efficiency [b] @ 25% rated power	%	60	60
Energy efficiency @ rated power	%	50	50
Power density	W / L	650	650
Specific power	W / kg	650	650
Cost [c]	$ / kWe	45	30
Transient response (10-90% of rated power)	Seconds	1	1
Cold start-up time to 50% of rated power			
@ - 20C ambient temp	seconds	30	30
@ + 20C ambient temp	seconds	5	5
Start-up and shut down energy [d]			
from - 20C ambient temp	MJ	5	5
from + 20C ambient temp	MJ	1	1
Durability with cycling	Hours	5,000 [e]	5,000 [e]
Unassisted start from low temperatures [i]	C	- 40	- 40

Source: USDOE Fuel Cell Technical Plan, 2007

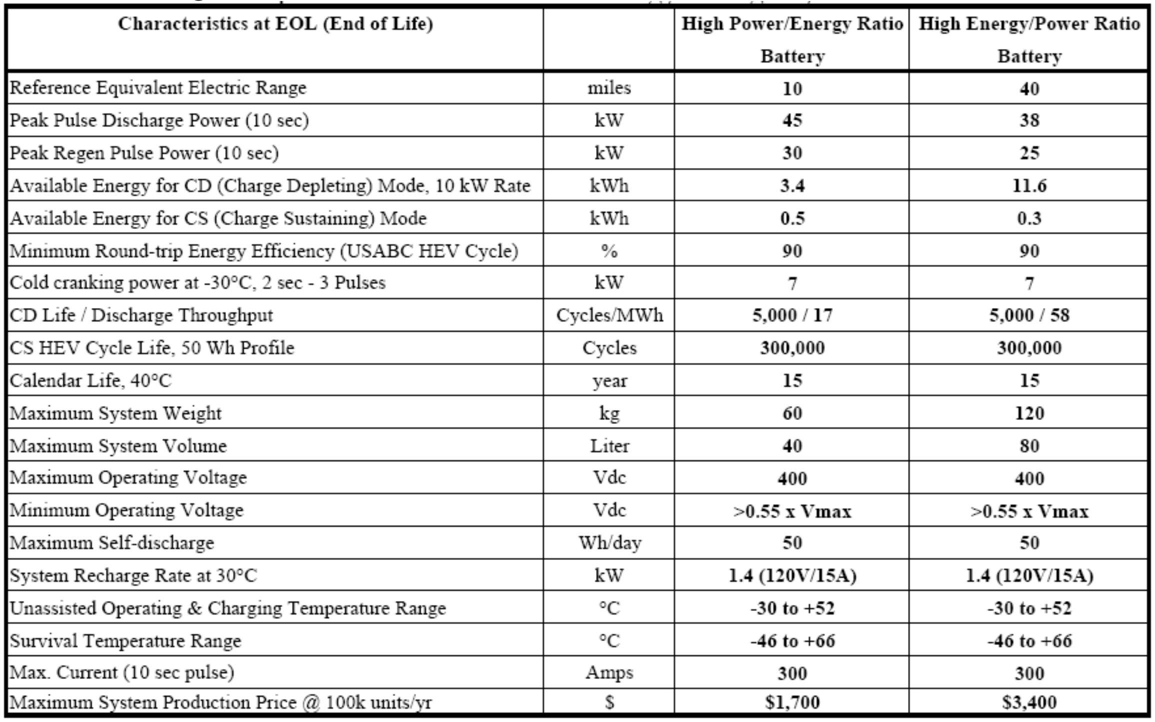
Notes

a. Targets exclude hydrogen storage, power electronics and electric drive
b. Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
c. Based on 2002 dollars and cost projected to high-volume production (500,000 systems per year)
d. Includes electrical energy and the hydrogen used during the start-up and shut-down procedures
e. Based on test protocol to be issued by USDOE in 2007
f. 8-hour soak at stated temperature most not impact subsequent achievement targets

APPENDIX C

US Advanced Battery Consortium Technical Targets

Technical targets for PHEVs



Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	**10**	**40**
Peak Pulse Discharge Power (10 sec)	kW	**45**	**38**
Peak Regen Pulse Power (10 sec)	kW	**30**	**25**
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	**3.4**	**11.6**
Available Energy for CS (Charge Sustaining) Mode	kWh	**0.5**	**0.3**
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	**90**	**90**
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	**7**	**7**
CD Life / Discharge Throughput	Cycles/MWh	**5,000 / 17**	**5,000 / 58**
CS HEV Cycle Life, 50 Wh Profile	Cycles	**300,000**	**300,000**
Calendar Life, 40°C	year	**15**	**15**
Maximum System Weight	kg	**60**	**120**
Maximum System Volume	Liter	**40**	**80**
Maximum Operating Voltage	Vdc	**400**	**400**
Minimum Operating Voltage	Vdc	**>0.55 x Vmax**	**>0.55 x Vmax**
Maximum Self-discharge	Wh/day	**50**	**50**
System Recharge Rate at 30°C	kW	**1.4 (120V/15A)**	**1.4 (120V/15A)**
Unassisted Operating & Charging Temperature Range	°C	**-30 to +52**	**-30 to +52**
Survival Temperature Range	°C	**-46 to +66**	**-46 to +66**
Max. Current (10 sec pulse)	Amps	**300**	**300**
Maximum System Production Price @ 100k units/yr	$	**$1,700**	**$3,400**

Source: US Advanced Battery Consortium (USABC)

Technical targets for BEVs

Parameter of fully burdened system	Units	Min goals, long-term commercialization	Long term goal
Power density	W / L	460	600
Specific power – discharge, 80% DOD/30 sec	W / kg	300	400
Specific power – regen, 20% DOD/10 sec	W / kg	150	200
Energy density – C/3 discharge rate	Wh / L	230	300
Specific energy – C/3 discharge rate	Wh / kg	150	200
Specific power / specific energy ratio		2 : 1	2: 1
Total pack size	kWh	40	40
Life	Years	10	10
Cycle life – 80% DOD	Cycles	1,000	1,000
Power & capacity degradation	% of rated spec	20	20
Selling price – 25,000 units @ 40 kWh	$ / kWh	<150	100
Operating environment	C	-40 to +50 [a]	-40 to +85
Normal recharge time	Hours	6 [b]	3 to 6
High rate charge		20 – 70% SOC in <30 min @ 150 W/kg [c]	40 – 80% SOC in 15 min
Continuous discharge in 1 hour – no failure	% of rated energy capacity	75	75

Notes

a. 20% performance loss (10% desired)
c. <20 min @ 270 W/kg desired
b. 4 hours desired

Source: US Advanced Battery Consortium (USABC)