Status and Prospects for Zero Emissions Vehicle Technology

Report of the ARB Independent Expert Panel 2007

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EXECUTIVE SUMMARY

1. Introduction

At the 2003 Zero Emission Vehicle (ZEV) Regulation hearings, the California Air Resources Board (ARB) directed staff to establish an independent expert review panel (Panel) to examine the status of ZEV technologies and to advise the Board. The Panel was constituted in early 2006 and carried out its work between May 2006 and March 2007. The overall objective of the Panel was to provide a thorough and accurate portrayal of the current status of sustainable zero emission vehicle technologies and the prospects for ZEV technology advancement in both the near-and long-term.

The Panel's work consisted primarily of extensive data collection followed by a critical assessment. Summaries of the data and the Panel's assessment are contained in this Final Report.

Starting in early May, the Panel engaged in an intensive effort to gather information on ZEV technology status, key technical issues, current and prospective materials and manufacturing costs and plans for evaluation/demonstration and commercialization of various ZEV and ZEV enabling technologies. This information was collected by soliciting responses to a series of questionnaires that were developed by the Panel, and through visits with key sources, including the leading developers of ZEV enabling technologies and the major automobile manufacturers.

The information collected by the Panel members underwent a thorough, critical assessment by the entire Panel in an effort to fully understand and accurately portray the current and likely near and medium term state of the art. Information from the various sources was compared and contrasted and, where gaps or discrepancies were identified, was followed up with selected sources in an effort to reconcile the information.

The Panel organized its efforts around three main ZEV enabling technologies –energy storage, hydrogen storage and fuel cells. Then, building on current status and prospects for further advances of these technologies and their integration into vehicles, the Panel attempted to forecast the prospects of zero and near-zero emission vehicles.

The Panel's key findings and conclusions are summarized below.

2. Vehicle Energy Storage Systems

The Panel's investigation focused on advanced battery technologies with potential to be fully developed and available for use in Hybrid Electric Vehicles (HEVs), Full Performance Battery Electric Vehicles (FPBEVs) and Plug in Hybrid Electric Vehicles (PHEVs) within the next 5-10 years. The principal findings and conclusions for the main candidate technologies are summarized below, followed by some observations on battery strategy and availability from the Panel's discussions with battery and automobile manufacturers.

A. Nickel Metal Hydride Batteries (NiMH)

High power NiMH technology for HEVs is now mature and mass manufactured in Japan in plants with capacities up to 500,000 systems annually. It is the conclusion of the Panel that high cost remains the greatest challenge for battery and HEV manufacturers, with an estimated cost (price to Original Equipment Manufacturers [OEMs]) of $2,000 for compact and $4,000 for a midsize HEV battery produced at a rate of 100,000 systems per year. These costs appear to account for much of the current price difference between hybrid and conventional vehicles. At a production rate of 1 million systems, battery costs are projected to drop to $1,300 and $2,500, respectively. Competition is expanding but market entry requires large investments for the required fully automated battery manufacturing plants.

Medium power/medium energy NiMH technology has promise to meet the technical requirements for PHEVs with relatively short (e.g., 10-20 miles) nominal electric range. It is the conclusion of the Panel that in mass production, medium power/medium energy NiMH technology's incremental cost over that of HEV batteries, estimated to be about $800-1,200, is probably less than the difference in lifetime fuel costs. However, no substantial efforts to develop or capabilities to fabricate medium power NiMH technology appear to exist.

High energy NiMH technology is still used successfully in FPBEVs manufactured by major automobile manufacturers under the ZEV program. It is the conclusion of the Panel, however, that energy density is fundamentally limited and marginal for FPBEV applications, and costs remain as high as or higher than in 2000 and are unlikely to decline. High energy NiMH technology for possible FPBEV applications has not advanced in recent years.

B. Lithium Ion Batteries (Li Ion)

Li Ion batteries are making impressive technical progress worldwide especially with regard to calendar and cycle life and safety, the areas of special concern for automotive applications. Promising new materials and chemistries are expanding the capabilities and prospects of all Li Ion technologies.

High power Li Ion technology for HEVs appears close to commercialization in the view of the Panel. A variety of materials, manufacturing techniques and companies are competing to achieve the performance and cost goals for this established battery application which increases the probability of technical and market success. Importantly, for HEV applications Li Ion batteries have potentially lower cost than NiMH because they promise to deliver the required power with smaller capacities and lower specific cost.

Medium energy/power Li Ion technology has sufficient performance for PHEVS and small FPBEVs, and it can be expected to meet the life requirements for FPBEVs, in the view of the Panel. Recent test results indicate good potential to also deliver the very demanding cycle life for PHEVs. The projected costs for shorter range PHEV Li Ion batteries are about $3500-4000 in mass production; this is generally less than the fuel cost savings expected over the life of the vehicle. Low volume cell production and prototype battery fabrication is underway in Asia and Europe, and limited fleet demonstrations are underway or planned.

High energy Li Ion technology has sufficient performance for small FPBEVs, and good potential to meet all performance requirements also of midsize and larger FPBEVs with batteries of modest weight (e.g., less than 250-300kg). Cell and battery technology designed for these applications are likely to also meet cycle life goals. It is the conclusion of the Panel, however, that battery cost remains high even in mass production, (probably near the levels projected in

2000), well in excess of expected lifetime fuel cost savings. While high energy Li Ion technology probably will benefit from general progress in Li Ion technology, no efforts seem underway to advance technology designed for FPBEV applications.

Batteries assembled from large numbers (typically, 5,000 or more) of small, high energy Li Ion cells mass-manufactured for laptop computers and other electronic applications are now being used in FPBEVs (and PHEVs) fabricated on a small scale. It is the conclusion of the Panel, however, that such small-cell batteries, although providing early opportunities to demonstrate the technical capabilities of PHEV conversions and modern FPBEVs, have inherently high costs and uncertain calendar and cycle life.

C. ZEBRA Batteries

The ZEBRA (sodium-nickel chloride) battery technology has insufficient power density for HEV and PHEV applications but meets the technical requirements for small FPBEVs. The batteries have been successfully demonstrated in small European FPBEVs, heavy duty vehicles and hybrid buses. The ZEBRA battery is likely to remain the lowest-cost advanced battery because of low materials costs and can be ordered now from its Swiss manufacturer in quantities of 1000s, with rapid expansion of production possible if demand develops. However, the Panel has not seen any automobile manufacturer interest in the battery, probably due to a combination of limited power density and the implications of high temperature operation.

D. Industry Strategies and Perspectives

Battery manufacturers' positions depend on their current technology capabilities and market positions. Mass-manufacturers of NiMH high power cells and modules for HEV batteries are focused on technology cost reduction and involved in capital-intensive production capacity expansions that assume increasingly competitive HEV mass markets exceeding 1 million vehicles by 2010. FPBEVs are not a target of their NiMH battery technology development efforts, and they consider PHEV battery requirements insufficiently defined to permit an assessment of NiMH technology and market prospects for this new application. No development activities appear underway to explore whether NiMH has technical potential for PHEVs.

Mass-manufacturers of Li Ion cells for consumer products are now engaged in the development of established Li Ion chemistries for HEV applications, with commercialization possible as early as 2008, and a vigorous market competition of technologies and manufacturers is likely to emerge. They do not appear to be pursuing development of Li Ion batteries for FPBEVs or for PHEVs. Li Ion battery costs are considered too high for FPBEVs and government financial incentives are thought unlikely to induce a large number of customers to buy vehicles of limited range. The major impediment to engagement in developing Li Ion batteries for PHEVs appears to be that the PHEV battery requirements are insufficiently defined at this time. GM's apparent interest in PHEVs (tied to Li ion availability) might stimulate efforts to develop Li Ion technology for PHEV applications. The Panel found no major battery manufacturer interest in high energy Li Ion batteries for FPBEV applications.

Several smaller companies in Europe and Japan have been developing medium and high energy Li Ion technologies, some of them based on advanced materials, chemistries and/or manufacturing techniques. Their strategy is pursuit of limited-volume applications and markets that may be emerging, especially in small Battery Electric Vehicles (BEVs) (including FPBEVs) and more recently also in PHEVs. Several of these companies hold the view that Li Ion-powered PHEVs and small BEVs will be able to attain life cycle cost competitiveness with conventional vehicles in urban fleet applications, and a few have established cell production capacities for hundreds to a few thousands of 10-25kWh batteries per year, sufficient for demonstration fleets. Most of these organizations are owned by large companies but the resources being invested in development and demonstration of batteries are still very modest. While the commercial prospects of BEV- and PHEV-design Li Ion technologies still seem unclear to them, several of these manufacturers noted that development of such technologies was likely to benefit from supported demonstration programs and/or financial incentives.

Automobile manufacturers' positions regarding batteries are determined largely by their extensive efforts to evaluate and advance the HEV-design Li Ion battery system technologies likely to be commercialized within the next few years. Confidence in the readiness of Li Ion batteries for deployment in mass-produced vehicles is growing but some concerns about life and safety remain. Based on their experience with the FPBEVs under the California ZEV initiative, most automobile manufacturers continue to hold the view that FPBEVs will remain niche vehicles, and no efforts to advance battery technologies for FPBEV applications are being supported by them at present. It remains to be seen whether recent announcements by Mitsubishi and Nissan of plans for introduction of BEVs are going to stimulate efforts to develop Li Ion batteries that meet the requirements of these vehicles.

The prospects of PHEVs also were judged negatively by most major automobile manufactures 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. In the U.S., an effort sponsored by DOE and supported by USABC is now underway with automobile industry expert participation to establish PHEV battery performance, life and cost targets for a planned Research and Development (R&D) program. In Japan the New Energy and Industrial Technology Development Organization (NEDO) is launching an initiative to develop PHEV batteries with the involvement of leading Li Ion battery developers. These initiatives and automobile manufacturers' initiatives such as GM's recently announced plans to offer a PHEV version of the Saturn VUE HEV and to launch the "Volt" PHEV if suitable Li Ion batteries become available are the signals needed by the major battery manufacturers to become engaged with their own resources in the development and manufacture of batteries for PHEVs.

3. Hydrogen Storage Systems

Storing sufficient hydrogen on a vehicle to power it for adequate distance, safely, and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the automobile industry and its suppliers. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one manufacturer identified it as the single greatest challenge.

Unlike other major technologies being pursued in support of ZEVs, hydrogen storage technologies have advanced relatively little in recent years. The primary system advancements have been in the area of improving compressed gaseous hydrogen storage and, to some extent, improving liquid hydrogen storage. However, in the last 3 to 4 years, as it became apparent that on vehicle fuel reformers for generation of hydrogen from carbon based liquid fuels were not a viable option, many alternative storage concepts have begun to receive significant research attention. A few concepts (e.g., metal hydrides and carbon nanotubes) that have been investigated at relatively low levels of effort for many years are now receiving increased attention. However, these efforts are fairly young and it is still too early to determine if they will result in technically and economically realistic hydrogen storage system alternatives.

A. Near Term Outlook

In the near term, the dominant form of storing hydrogen onboard light vehicles will continue to be compressed hydrogen gas. With the exception of BMW, every other OEM contacted indicated that this was the only realistic short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. All the other OEMs preferred 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly provide almost 50% more range. Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage is being demonstrated as workable but with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel.

An important issue with any of the short term hydrogen storage options is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen.

Cost is another important issue, especially for the short term since none of the storage systems are produced in sufficient volumes to allow significant production economies of scale. While none of the OEMs gave specific current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to cost $10,000 or more each for both liquid and compressed gas storage.

B. Longer Term Outlook

For the longer term, some of the alternative storage technologies being researched may prove to be effective. Both solid and liquid carriers are being researched with hydrogen “recharging” being carried out both onboard and off of the vehicle. There don’t appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire provided projections for complete system performance or costs. It appears to be too early to make reasonably accurate projections.

C. Conclusions of the Panel

It is the conclusion of the Panel that on-board hydrogen storage is a major challenge for hydrogen fuel cell vehicles. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen gas storage which has problems providing sufficient vehicle range without excessive volume, weight, and cost.

The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or design modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center “tunnel” is located and/or replacing rear coil springs with leaf springs to increase space available for hydrogen tanks. Thus, depending on the type of vehicle and system efficiency, it seems likely that sufficient compressed hydrogen could be stored on a vehicle to provide a range in excess of 200 miles, perhaps reaching 300 miles or more.

Liquid hydrogen storage technology appears to have advanced sufficiently that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range.

However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. Assuming that at least 5 kg (165 KWh) of hydrogen will be needed to provide sufficient vehicle range, the cost would be $1650 even with the lowest TIAX tank cost estimate. For liquid storage, the cost would be even higher. There is little expectation that the cost of either of these systems will go much lower even with higher volumes.

The weight outlook is better than the cost outlook. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5 kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither TIAX nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, the capacity to contain well over 6% hydrogen. However, the remainder of the support system could have a huge effect on both cost and weight fraction.

4. Automotive Fuel Cell Systems

Automotive fuel cell technology continues to make substantial progress but is not yet proven to be commercially viable. Technological and engineering advancements have improved, simplified and even eliminated components of the fuel cell system. Progress made since the 1998 ARB fuel cell report include major improvements in the membrane electrode assembly (MEA) and fuel cell stack technologies. The Balance of Plant has a reduced number of components and now uses some parts that are of automotive quality and cost. The fuel cell system has a reduced start time and in-vehicle start-up from a frozen condition has been demonstrated. Great strides have been made in the science of materials and operating characteristics of fuel cells. This increase in fundamental understanding shows promise for solving life, abuse and durability issues for fuel cell systems.

The consensus among the majority of fuel cell system developers is that in order to achieve commercialization there are simultaneous requirements for:

1) Higher MEA power per unit area of fuel cell electrodes (goal of 0.8 to 1.0 W/cm^2)
2) Reduced MEA catalyst cost (goal of total MEA catalyst loading <0.1 to 0.5 mg Pt/cm^2)
3) Longer fuel cell system operating life and increased durability (goal of >5000 hours of

customer use)

4) Proton Exchange Membrane (PEM) materials that are stable and can operate at a higher temperature (above 100^{o}C)
5) Engineering advances

An increase in MEA specific power allows a given fuel cell stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, at a given voltage, decreases in inverse proportion to MEA specific power. The MEA catalyst cost is directly related to the price of platinum. The price of this noble metal is rising due to world wide demand exceeding supply and at current levels it represents a significant barrier to automotive fuel cell commercialization. The life and durability of fuel cells in automotive applications is not yet proven. A life of 5000 + hours in a light duty vehicle type load cycle has not been demonstrated at the cell or stack level. The development of high temperature membranes can potentially reduce the size and complexity of the Fuel Cell Electric Vehicle (FCEV) thermal system and may possibly eliminate the need for stack humidification. Engineering advances and innovation are focused on materials, stack design, and balance of plant to reduce cost and increase life.

Overall, the Panel concludes that at this time no fuel cell developer has achieved the necessary requirements for automotive fuel cell commercialization. The developers are relying on future technological improvements to meet both cost and life goals. Achieving these goals creates some contradictory requirements for the fuel cell system. The Panel believes that these requirements are difficult to achieve separately and because they are interrelated, even more difficult to solve simultaneously. These technological improvements include the development of MEAs that use significantly less catalyst material and that operate at higher specific power and temperature over a longer system life. To simultaneously increase performance, extend life and reduce cost will likely take ingenuity and invention.

Each of the developers believes that the simultaneous requirements can be met but on different time schedules. For example, one major developer’s objective is to compete with the “upper” segment of internal combustion engine (ICE) vehicles in the year 2020 at volumes of 100,000 units per year. Another major developer’s assessment is that a commercially viable fuel cell system would be available in 2010, if a production rate of 500,000 units per year could be realized.

At this time, large conventional suppliers to the automotive industry are not active in fuel cell development and are taking a wait and see attitude. If the market develops, it is conceivable that they will rapidly acquire the technology.

The Panel remains cautiously optimistic regarding the prospects for fuel cell system commercialization. There are still large technical barriers to be solved but these might well be overcome over the next 5-10 years through massive efforts underway at the major fuel cell and automobile manufacturers. However, there are other issues that are beyond the control of any single manufacturer. Wide spread deployment of FCEVs will require continuous strong support and a long term commitment from government agencies in resolving there issues. These include timely availability of adequate and affordable hydrogen refueling, as well as need for a host of sustainable financial incentives to help minimize the capitalization risks of all key stakeholders during the early years of initial commercialization of hydrogen powered FCEVs.

5. Vehicle Integration – Automotive Manufacturers

The status and prospects of vehicle integration of zero emission vehicles (ZEVs) by ten major original equipment automotive manufacturers (OEMs), as well as their advanced technology vehicles (ATVs) that could have synergistic benefits supportive to the introduction of ZEVs, are summarized below. In addition to vehicle technical considerations, vehicle business considerations (e.g., manufacturing cost, capital investment, marketability, etc.) also are addressed, in order to forecast the future prospects, introduction timing, and volume milestones of the ZEV and ATV technologies.

A. Full Performance Battery Electric Vehicles (FPBEVs)

Full Performance Battery Electric Vehicles are defined in this report as BEVs fully capable of high speed U.S. urban/suburban freeway driving.

Despite substantial technology progress, prior efforts to introduce FPBEVs were unsuccessful due to high manufacturing cost (primarily the battery) and limited mass market customer acceptance due to limited range and long recharge time, and there has been little progress since. Specifically, the large batteries required to provide the necessary driving range, as well as an acceptable “cushion”, remain very expensive.

Higher fuel prices and less demanding driving conditions in Japan and Europe provide lower barriers to success and as a result a few OEMs are developing small FPBEVs with Li Ion batteries for these markets, and they may bring them to the U.S. as niche vehicles.

It is the Panel’s opinion that FPBEVs are not likely to become mass market ZEVs in the foreseeable future due to the high cost for the battery not being recoverable with fuel cost savings and limited customer acceptance due to range and recharge time issues.

B. City Electric Vehicles (CEVs)

City Electric Vehicles are defined in this report as BEVs with limited acceleration and top speed (e.g. 50/60 mph) and thus not suitable for high speed U.S. urban/suburban freeway driving, although at present they must meet all Federal Motor Vehicle Safety Standards (FMVSS) requirements. These performance limitations allow a smaller size battery and lower power electric drive system, so that the vehicle can have a lower manufacturing cost and thus be made more affordable to the customer.

Prior efforts to produce CEVs were unsuccessful due to high cost and limited mass market customer acceptance and there has been little progress since. A special CEV FMVSS similar in concept to FMVSS 500 (e.g., restrict CEVs from freeway driving, etc.) may help stimulate development in the U.S.

It is the Panel’s opinion that CEVs are more likely to become future mass market ZEVs in Japan and Europe than in the U.S. due to performance limitations.

C. Neighborhood Electric Vehicles (NEVs)

Neighborhood Electric Vehicles are defined in this report as BEVs capable of top speeds between 20 and 25 mph that meet FMVSS 500 and are limited to roads with posted speeds of

35 mph or less.

NEV technology appears to be commercially successful but has low volume potential due to limited applicability. Also, because they use very simple technology, NEVs have very little synergy with larger BEVs.

It is the Panel's opinion that NEVs provide no significant technical benefits to future mass market ZEVs due to their simple technology and performance limitations.

D. Hybrid Electric Vehicles (HEVs)

HEVs have no customer compromises and therefore appeal to mass market customers willing to pay a premium. While producers are driving down the costs of electric drive components and systems, high manufacturing cost is still an issue. However, OEMs are introducing many new entries, despite the cost issue, mostly for competitive reasons. Overall, HEV sales volume rises and falls with the price of gasoline – making future growth forecasts uncertain.

It is the Panel's opinion that HEVs, due to their success, are providing major support to future mass market ZEVs by continuing to stimulate advances in electric drive systems, electric accessories, and battery technologies. Also, they are increasing customer awareness of electric drive technology and the associated benefits.

E. Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs have no expected customer compromises while promising several benefits to customers and society. The relatively small battery capacity can be fully used daily for maximum customer fuel savings payback of the initial vehicle premium.

Recently, some OEMs have become interested in PHEVs, and GM and Ford have shown concept PHEVs at recent auto shows and other events – which is attracting major media attention and establishing high consumer expectations.

However, definitions and fuel economy/emissions testing standards do not yet exist and need to be agreed upon. Also, All Electric Range (AER) could have a major impact on manufacturing cost, as well as capital investment requirements if unique and more powerful electric drive systems are necessary, and therefore AER could have a significant impact on the early success of the technology.

Despite the fact that recent auto show PHEVs appeared to require new platforms, it may be more likely that OEMs will want to derive early PHEVs from existing HEVs in order to minimize capital investment and the associated business risk. For the same reason, blended AER, as opposed to EV mode, may be more likely in early products.

It is the Panel's opinion that PHEVs have the potential to provide significant direct societal benefits and are likely to become available in the near future. They may foster future mass market BEVs by stimulating energy battery development and conditioning mass market customers to accept plugging in.

F. Fuel Cell Electric Vehicles (FCEVs)

FCEVs are considered the ultimate solution by several OEMs with massive R&D efforts underway. However, simultaneously achieving performance, durability and cost objectives with FCEVs continues to be very difficult.

The cost, weight, and volume of adequate vehicle hydrogen storage and availability of a hydrogen infrastructure are major issues.

Plug-in series hybrid FCEVs operating “steady state” have potential to simultaneously achieve performance, durability and cost objectives.

It is the Panel’s opinion that with the past rate of success and the massive intellectual and financial resources being devoted to this technology, FCEVs continue to be a promising candidate for a future mass market true ZEV.

G. Hydrogen Internal Combustion Vehicles (H2ICVs)

H2ICV technology is not widespread and is only being pursued by two OEMs – BMW and Ford. This technology entails fairly simple conversions of conventional powertrains, with relatively low manufacturing costs and capital investment requirements. However, the hydrogen issues are the same for infrastructure and worse for onboard storage than for FCEVs. Also, while they have very low emissions, H2ICVs are not true ZEVs.

It is the Panel’s opinion that H2ICVs could provide minor benefits to future mass market ZEVs (FCEVs), limited to onboard vehicle hydrogen storage and hydrogen infrastructure, but the Panel also cautions that if the relative incentives change there could be a shift in resources away from FCEV development to fund H2ICVs.

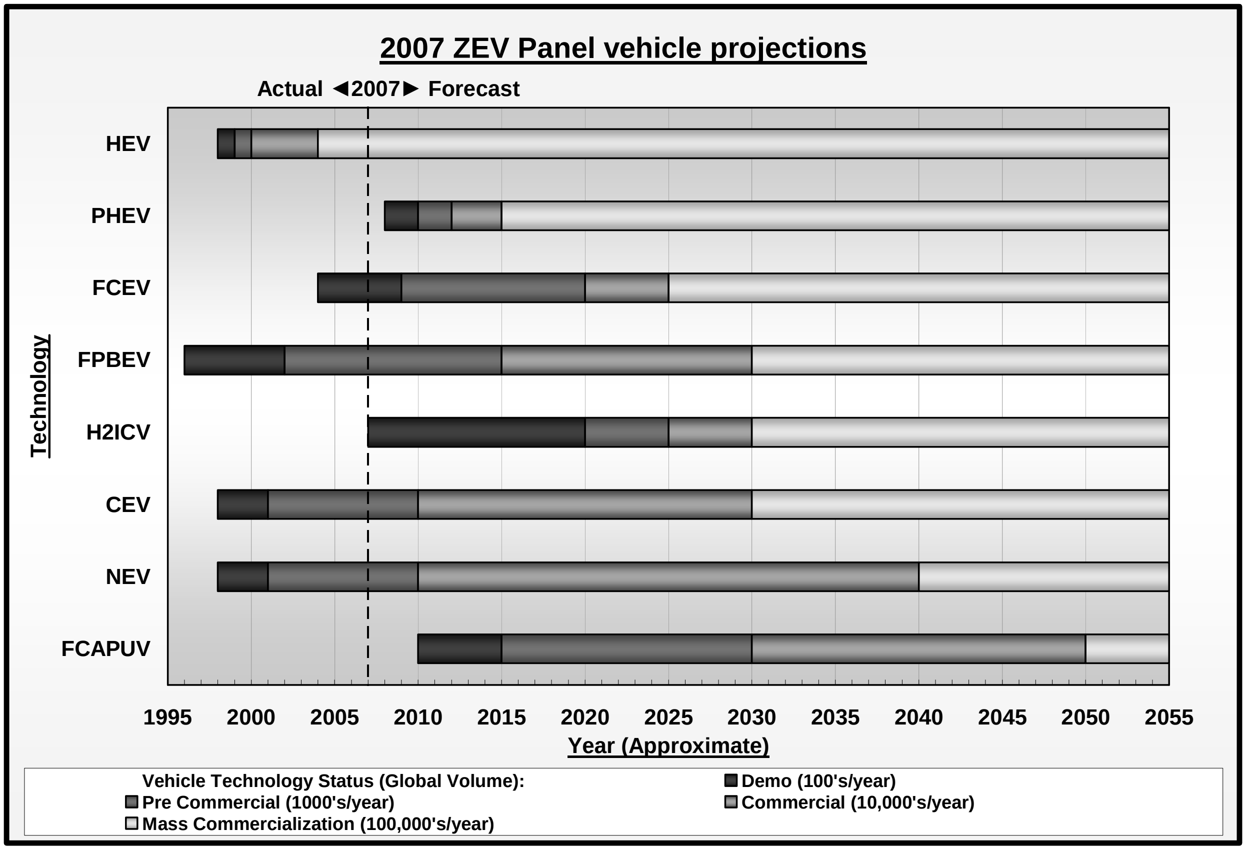
H. Fuel Cell Auxiliary Power Unit Vehicles (FCAPUVs)

FCAPUV technology is not widespread and is only being pursued by one OEM – BMW. The Hydrogen Proton Exchange Membrane (PEM) system in a H2ICV is the most likely application but this is operationally different from a FCEV.

It is the Panel’s opinion that FCAPUVs are unlikely to provide any significant benefits to future mass market ZEVs.

6. Overall Conclusions: The Prospects of ZEVs

The bottom line question posed to the Panel by the ARB was “what is the approximate timeframe in which the Panel expects the various ZEV and ZEV enabling technologies to achieve the Demonstration stage (100s of vehicles per year), Pre-Commercialization (1000s of vehicles per year), Early Commercialization (10,000s of vehicles per year) and finally Mass Commercialization (100,000’s of vehicle per year). Of course, a precise answer to this question is very difficult as it depends upon many factors which are impossible to foresee at this time. The chart below reflects the Panel’s consensus projection on global volumes, based on today’s automotive environment, including the present ZEV regulations, and barring any sudden and unanticipated major trigger events (e.g., scientific breakthroughs, trends and actions such as further major increases in gasoline taxes (U.S.) and/or reduced gasoline availability driven by major disruptions in petroleum supply, increasingly dramatic evidence of climate change, war, terrorism, etc.):



The Panel suggests that these time projections while necessarily uncertain regarding the exact years of implementation carry somewhat greater confidence in the relative timing of these technologies for the reasons outlined in this report and briefly summarized here:

> *The Panel's projection is that PHEVs with modest energy storage capacity will be derived from HEVs and will proliferate rapidly, stimulating further development and cost reduction of energy batteries and leading to commercially viable PHEVs and, in the longer term, FPBEVs. While PHEVs will continue to grow rapidly, as they have no functional limitations, FPBEVs will grow more slowly due to customer acceptance of limited range and long recharge time. NEVs are commercially viable now and will continue to grow, but will grow slowly due to limited functionality. CEVs will become commercially viable in Japan and Europe in the not too distant future due to lower hurdles for BEVs to overcome. CEVs may be offered in the U.S. as energy batteries continue to mature, but growth will be slow due to functional limitations of BEVs in general, and the specific limitations of CEVs, especially urban freeway driving. The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 time frame, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure. If that happens, FCEVs will grow rapidly, followed by some H2ICVs, and some H2ICVs with FCAPUs.*

As a long term ZEV outcome, the Panel can envision plug-in hybrid FCEVs, powered by sustainable electricity for shorter trips and sustainable hydrogen for longer trips.

Glossary of Terms, Abbreviations and Symbols:

APU	auxiliary power unit
ARB	Air Resources Board (California, CARB)
ATPZEV	Advanced Technology Partial Zero Emission Vehicle
BEV	battery electric vehicle
CEV `	city electric vehicle
CH2	compressed hydrogen
CNG	compressed natural gas
CO	carbon monoxide (contributor to air pollution)
CO2	carbon dioxide (greenhouse gas)
Cold FTP	driving schedule conducted in 20^{o}F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
Combined	vehicle fuel economy – prior to 2008 MY: harmonic average of FTP and HFET weighted 55/45% respectively; can be applied to adjusted values or unadjusted values ("C-H", "M-H")
Consumption	vehicle fuel consumption – quantity of fuel or energy consumed divided by distance traveled (e.g., litres/100 kilometers, Wh/mile)
CVT	continuously variable transmission
CY	calendar year
DOD	depth of discharge (battery)
DOE	United States Department of Energy
DOT	United States Department of Transportation
Economy	vehicle fuel economy – distance traveled divided by quantity of fuel or energy consumed (e.g., miles/gallon, miles/kWh)
EDF	Electricitè de France
Efficiency	output energy divided by input energy, expressed as a percentage
EPA	United States Environmental Protection Agency
EPRI	Electric Power Research Institute
ETS[1]	electrical traction system (direct current to torque out)
EV	electric vehicle
FC	fuel cell
FCAPU	fuel cell auxiliary power unit
FCAPUV	fuel cell auxiliary power unit vehicle
FCEV	fuel cell electric vehicle
FCPS[1]	fuel cell propulsion system (hydrogen fuel in to torque out)
FCS[1]	fuel cell system (fuel cell stack + balance of plant for H2, air, coolant supply)
FPBEV	full performance battery electric vehicle
FMVSS	Federal Motor Vehicle Safety Standards
FTP	Federal Test Procedure; UDDS followed by first 505 seconds of UDDS ("FTP75", "EPA75")
GVWR	gross vehicle weight rating
H2	hydrogen
H2ICV	hydrogen internal combustion vehicle
HC	hydrocarbons (contributors to air pollution)
HEV	hybrid electric vehicle
HSS[1]	hydrogen storage system
HFET	Highway Fuel Economy Test (dynamometer driving schedule)
ICE	internal combustion engine

ISO	International Organization for Standardization
Label	vehicle fuel economy – prior to 2008 MY: city label = FTP x 0.9; highway label = HFET x 0.78 (“window sticker”)
LEV	low emission vehicle
LH2	liquid hydrogen
LHV	lower heating value (for calculating energy content of fuels used in vehicles)
Li Ion	lithium ion (battery)
Mass-Market	buyers that make up the majority of the (automotive) customer base, primarily interested in price/value/convenience, not hobbyists/enthusiasts
METI	Japanese Ministry of Economy, Trade and Industry
MY	model year
n/a or n.a.	not available (at publication of report)
NEV	neighborhood electric vehicle
NHTSA	National Highway Traffic Safety Administration (part of DOT)
NiMH	nickel-metal hydride (battery)
NOx	oxides of nitrogen (contributors to air pollution)
NREL	National Renewable Energy Laboratory (part of DOE)
OEM	original equipment automotive manufacturer
Panel	2006-2007 ZEV Technology Review Expert Panel (contractors to ARB)
PEM	polymer electrolyte membrane, or proton exchange membrane (fuel cell)
PbA	lead-acid (battery)
PHEV	plug-in hybrid electric vehicle
RESS[1]	rechargeable energy storage system (battery, ultra capacitor, flywheel, hydraulic)
SAE	Society of Automotive Engineers
SC03	driving schedule with air conditioning operating and 95°F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
SMUD	Sacramento Municipal Utility District
SOC	state of charge (battery)
SULEV	super ultra low emission vehicle
TBD	to be determined (before finalizing report)
UDDS	Urban Dynamometer Driving Schedule (“LA4”, “city test”)
UEV	utility electric vehicle
ULEV	ultra low emission vehicle
US06	driving schedule containing aggressive acceleration and high speeds (part of fuel economy label value for 2008 MY vehicles)
USABC	United States Advanced Battery Consortium
USCAR	United States Council for Automotive Research
VESS	vehicle energy storage system (section 3)
VFCS	vehicle fuel cell system (section 4)
VHSS	vehicle hydrogen storage system (section 5)
V2G	vehicle to grid (discharging electric vehicle battery energy into electric grid)
VOC	volatile organic compound (contributor to air pollution)
ZEV	zero emission vehicle

1. ISO term (electric vehicles)