Testimony for Congress
The House of Representatives Committee on Gov. Reform
Subcommittee on Energy and Resources
on the
Environmental Benefits, Cost Effectiveness, Market Penetration/Incentives, and US Manufacturing Capacity
of
Hybrid Electric and Plug-In Hybrid Electric Vehicles

By

Professor Andrew A. Frank
University of California-Davis
Dept. of Mech. Aero. Eng.
One Shields Ave, Davis, CA 95616
Tel:530 752 8120, fax: 530 752 4158

This report is written for the House of Representatives, Congress of the United States, Committee on Government Reform, Subcommittee on Energy and Resources for testimony to be given on July 20, 2006 at 2 pm.

This report will assume the Congress is already informed on the concept of the Hybrid Electric Vehicle (HEV) and the more advanced Plug-In Hybrid Electric Vehicle (PHEV).

I will briefly describe the difference between the HEV and the PHEV. The PHEV is not simply a HEV with more batteries. It can only be successful if the larger battery capacity is integrated with a bigger electric motor and a smaller gasoline engine. The results, shown in the figures below indicate fuel economy improvement of 50% over a conventional hybrid and 100% over a conventional car when using gasoline only after it has depleted it's battery to the maintenance state of charge (SOC) of around 20%. This is also dependent on the size of the battery pack.

In addition the PHEV needs only a 120 volt 15 amp standard GFI plug and circuit to charge. Thus the charger can become very low cost and use commonly available standard electrical outlets. This can be implemented for the smallest vehicle to the largest SUV. The PHEV is dependent on the driver to plug in the vehicle to reap the full benefits of displaced fuel. The driver of these cars will find a plug whenever they are parked because the cost of electricity to run these cars is about ¼ the cost of buying gasoline at $3.00/gallon for gasoline. They already use ½ the gasoline per mile after the batteries are depleted. Thus, the proper metric to judge the PHEV is the total gasoline fuel used for annual driving and the total electricity used annually. This metric has not yet been set by the USDOE and USEPA. This and other regulatory items will have to evaluated by EPA and other regulatory sources for the PHEV since it uses two energy sources.

A two year study published in 2001 by the Electric Power Research Institute (EPRI) under the guidance of a joint task force consisting of University, Federal Government Laboratories, Auto Industry, State Agencies, and Electric Utilities, Titled: "Comparing Hybrid Vehicle Options" will be referenced for the data presented in this report.

I have been researching Hybrid Electric Vehicles for the last 30 years and have constructed over a dozen such vehicles to prove the principal of increased fuel economy and performance and decreased emissions and green house gasses. These vehicles were constructed to show that the technology is feasible and cost effective if properly implemented. We have demonstrated in the vehicles that there is at least one way to build PHEV's that get double the fuel economy of the conventional car but yet provides greater performance and much lower operating costs.

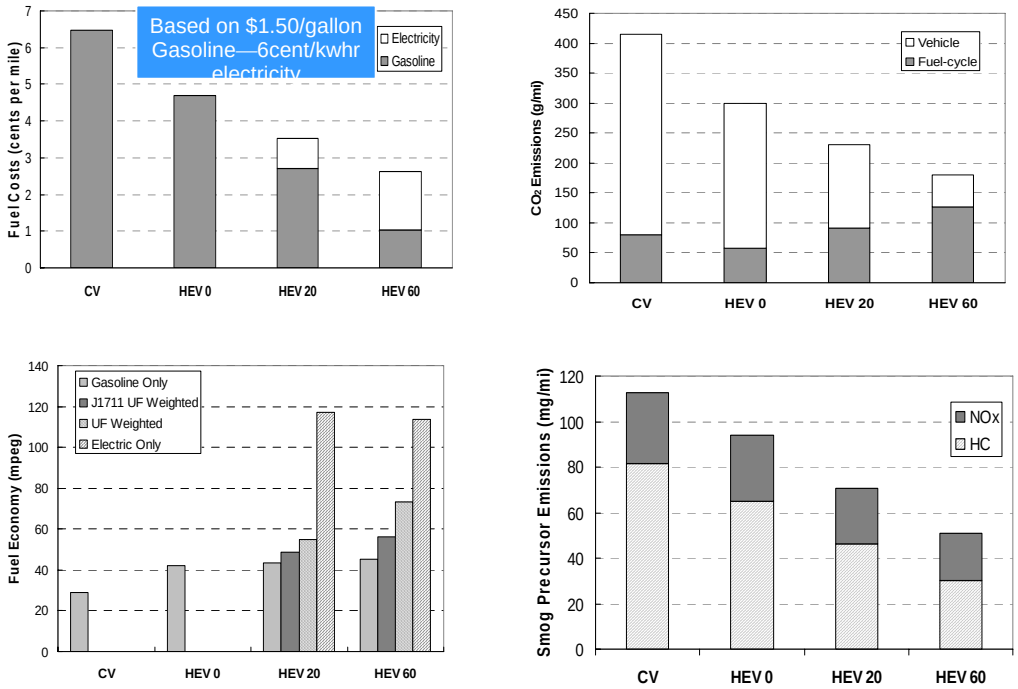
As a result of my experience with the USDOE National Labs Argonne, and NREL, DARPA, and many of the car companies both domestic and abroad, I have developed the knowledge of the technology choices that are currently available and the technologies necessary to manufacture the components and produce the vehicles for mass consumption. In particular, the HEV and PHEV concepts in this report are all to be built on conventional vehicle platforms from compact to full size sedans, (Example, Ford Focus to the Ford 500), and small SUV's and vans to full size Pickup trucks and SUV's, (Example, Ford Escape to the Ford Expedition).

The emissions and gasoline reduction of these vehicles are summarized in the collection of Figures below.

(The HEV20 and HEV60 are PHEV's with 20 and 60 miles of electric drive capability on the Federal Urban Driving Cycle, FUDC. This is the driving cycle used by the US EPA for emissions and fuel economy rating of all light duty vehicles, the CV means Conventional Vehicles and the HEV0 is equivalent to a Toyota Prius.)

The first figure shows 4 graphs depicting the Fuel costs based on $1.50/gallon Gasoline at the time of the study and the cost of electricity @ 6cents/kwhr from the California Electric Utility Grid, the CO2 green house gases, the equivalent miles per gallon and the smog precursors.
These graphs constructed by simulation for a 3300 lb family sedan the size of a Chevrolet Lumina or Ford Taurus.

Results: EPRI-Car Co's.-DOE Labs study "Comparing Hybrid Electric Vehicle Options"– for a 1500kg car



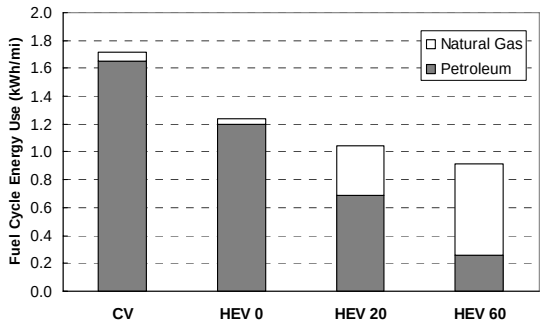
The legend and nomenclature for these graphs are as follows:

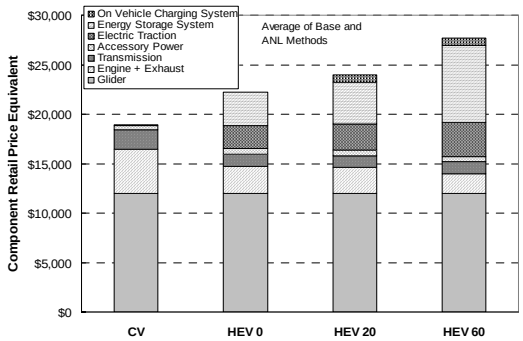
CV-----conventional gasoline vehicle
HEV0 -----zero electric range hybrid like a 2006 Toyota Prius
HEV20-----20 mile electric range PHEV plug-in hybrid
HEV60-----60 mile electric range PHEV plug-in hybrid

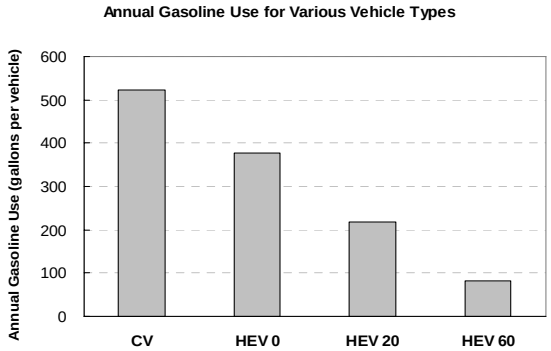
The vertical legends are:
cents per mile----Total for driving including electric & gasoline costs in 2001 in California.
g/mi----grams per mile of CO2 from the vehicle and fuel processing.
mpeg-----miles per equivalent gallon (converting all energy to equivalent gasoline).
mg/mi-----milligrams per mile of smog precursor emissions.

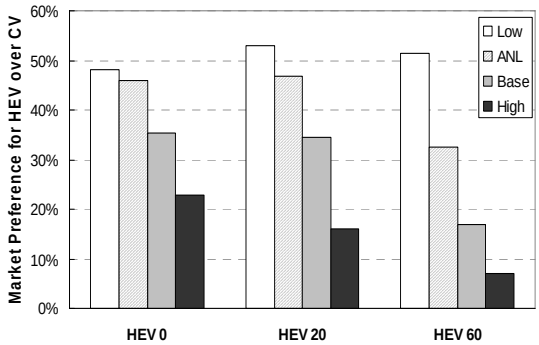
The next figure following shows the total energy used by the various battery size vehicles, the component costs as of 2001, the annual fuel consumed for 12,000 miles of travel, and the market preference from a survey of 400 randomly selected people from around the 50 States. All these calculations were for **fully integrated vehicle systems**, not just more batteries in a same vehicle platform. All these integrated vehicles are almost the same weight, within 100 lbs of the Conventional Vehicle, or CV.

EPRI study: Fuel, Running, Component and Purchase Costs, and Market Potential for Midsize 1500 kg car, in 2001,@ 100,000/year







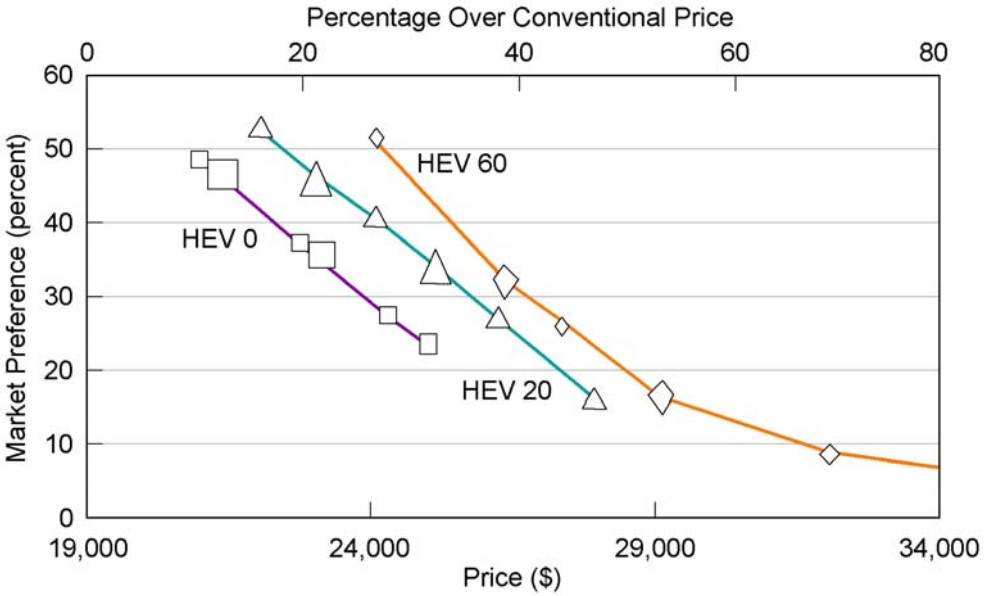


Legends for this set of graphs:

Kwhrs/mi---- kilowatt hours per mile of energy converted from gasoline and Natural gas (It was assumed that marginal electricity used to charge these vehicles is provided by Natural gas in California)
Component Retail Price Equivalent ---- Dollar prices of components for a complete vehicle estimated by the study group and Argonne National Laboratory
Gallons per vehicle----Gallons of gasoline used by a 1500 kg vehicle in one year of driving 12,000 miles.
Market preference for HEV over CV---- Percentage of new car sales if vehicles are priced low, ANL(Argonne National Lab), base (group consensus), and high. This chart was based on a survey of 400 people across the country.

The next figure indicates the price elasticity of the various hybrid options from a survey of 400 random people from across the US. This figure shows that people are willing to pay for more batteries and a longer zero emission all electric range and the better resulting fuel economy. These curves do not include such benefits as personal Solar or Wind Energy charging etc..

Mid-size HEV car Market Potential vs. Price



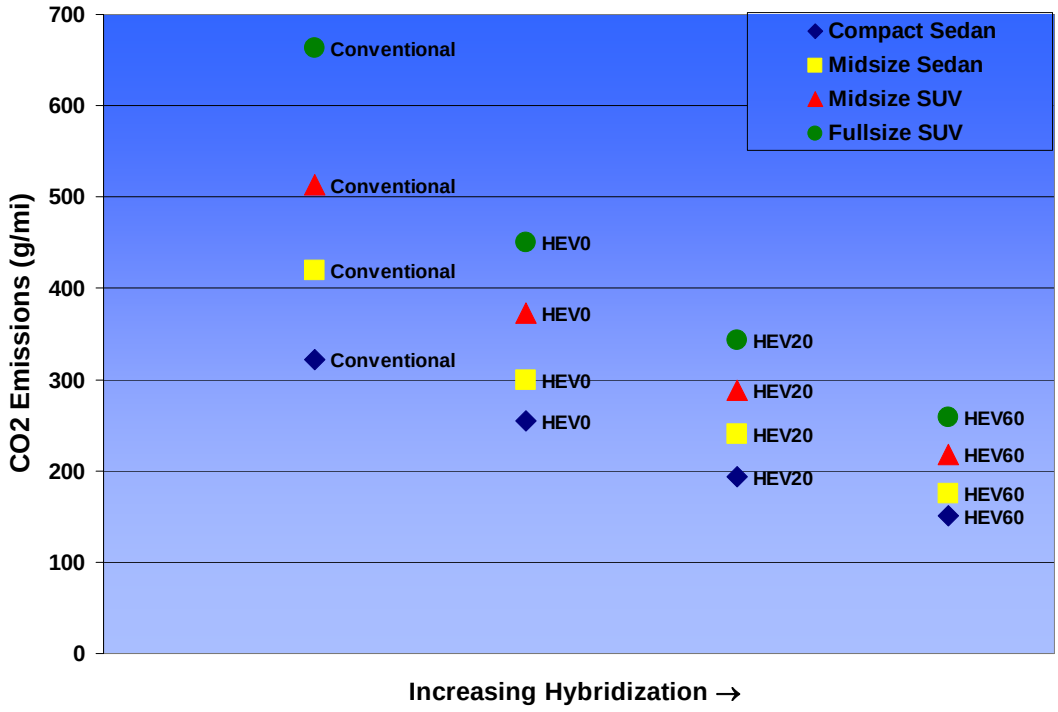
Legend:
Horizontal scale is retail price for the vehicles. The base 2001 vehicle is $19,000. Vertical scale shows percent of new car sales based on a survey of 400 people. The curves show the price-volume relationship of the vehicles and will help determine the subsidy needed obtain a new car penetration percentage for a mid size family sedan.

This set of curves indicate how the pricing of these vehicles will affect the sales volume compared to the conventional car of identical size and performance. For example to achieve a 50% penetration the retail price of a 60 mile range PHEV must be priced at about $5000 over the conventional vehicle. The reason for this is because the people in the survey are willing to pay d=for the additional features of the PHEV such as going to the gas station only 4 times a year versus 35 times a year in a conventional car.

Other features that have been developed since this study will give the PHEV even more value. For example, the integration of the PHEV with solar panels and small wind turbines on the roofs of the home and office will give the user energy independence over the electric grid and the gas station. This feature and other newly developed uses for the PHEV has not been included thus the results shown are conservative, and people will likely pay more for the PHEV.

The next curve show the green house gas emissions for all classes of light duty passenger vehicles, pickup trucks and SUV's.

Greenhouse Gas Emissions for all light duty cars trucks, SUV's



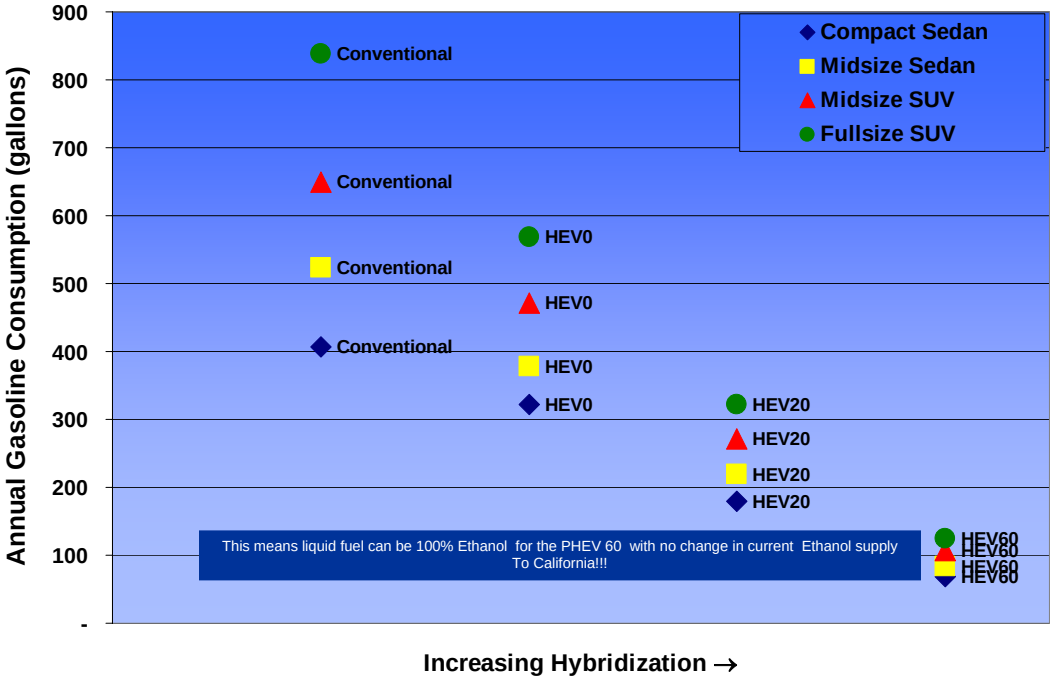
Legend:
g/mi----total grams per mile of CO2 emissions including fuel processing for both gasoline and electricity from the California electric grid.
Compact sedan----like a Ford Focus
Midsize Sedan----like a Ford 500
Midsize SUV----like a Ford Explorer
Fullsize SUV----like a Ford Expedition

The figure shows that as the all electric range, AER, increases the CO2 emissions from all light duty vehicles will decrease using the current electric grid in California and the emissions from currently certified gasoline engines. In other parts of the country which use more coal fired Electric plants the CO2 reduction is less but it is still significantly lower than the conventional car. Clean coal, new coal plants and renewable energy from wind and solar will, of course, greatly reduce the CO2 production from the PHEV and indeed may drive it to near zero.

The next graph shows the effect on gasoline use for all classes of vehicles currently in our market. The trend shows that the large battery vehicles can have a profound effect on the total fuel consumed in a year. This graph illustrates that the assessment of fuel consumption for the PHEV can no longer be judge on a simple 7.5 mile driving cycle as

current gasoline and HEV cars are currently evaluated. This means that new measures and test procedures need to be developed to judge the merits of the PHEV.

Annual Gasoline Consumption for 12,000 miles of driving-all L/D vehicles



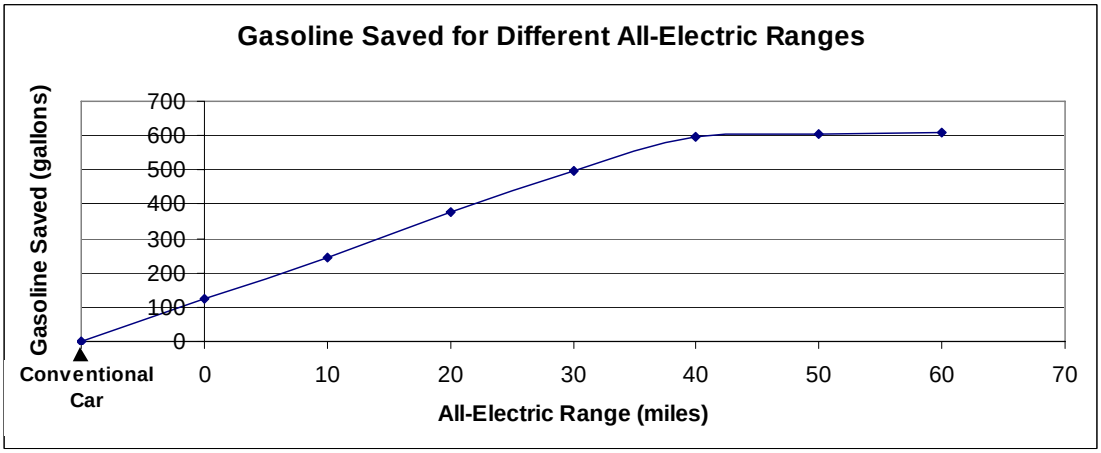
Legend:

Gallons---- gallons of gasoline used annually for 12,000 miles of driving for the various classes of vehicles.

This figure shows that "we can have our cake and eat it too" because it shows that the full size SUV PHEV60 will use less than ¼ the fuel of a compact sedan annually. The PHEV20 will use approximately 3 times more fuel annually than the PHEV60. Thus it is concluded that to have the greatest impact on oil consumption in the USA it is necessary to build PHEV' at 40 to 60 miles of all electric range, AER.

The following figure gives the relation of fuel saved by comparing an **average** conventional gasoline vehicle to various comparable size PHEV's with varying AER. It is shown that if we calculate the fuel used by these vehicles, and subtract it from the fuel consumed by the average CV which is 740 gallons a year for 15,000 miles of travel, then we obtain the fuel saved per year for various AER types of comparable PHEV's. From this we can calculate the annual fasoline consumption of the American fleet of cars and SUV's.

Annual Gasoline saved for the average car & Truck, Conv., HEV, PHEV's as a function of AER on FUDC (suggested standard for AER specification)
Conventional car uses 740 gals gasoline/yr.



Annual oil savings for 10% fleet penetration (PHEV-40) is about 300 million barrels saving 4.5% of the US oil used/year—Enough to Eliminate Middle Eastern Oil Imports !!
Use of Ethanol in PHEV's further increases oil savings!!
The best concept is to construct PHEV's with flex fuel capability.

Legend: This chart was constructed in January 2006 using latest data on vehicle use.
Conventional car---- is the average of light duty vehicles which consume 740 gallons of gasoline a year for 15,000 miles of travel.
Gallons saved----is the gasoline saved annually over 15,000 miles
All Electric Range----AER is the electric range for a PHEV (Notice zero AER is a HEV0 or a conventional hybrid like a Toyota Prius.)

These charts answer the following questions.

1. Cost effectiveness of the HEV and PHEV
2. Market Penetration potential of the HEV and PHEV
3. Environmental benefits of the HEV and PHEV
4. Oil saving potential of the HEV and PHEV

In general, they show that the larger the battery system the greater the benefits but according to the costs estimates of 2001 the greater the cost in quantities of 100,000 vehicles a year.

It should be noted that as the batteries are increased for longer AER in the PHEV, the electric motor power is also increased and the gasoline engine is decreased proportionally for the same performance. Surprisingly the weight is nearly the same as the batteries are increased for AER since the gasoline engine becomes smaller and lighter and the vehicle powertrain becomes simpler and less complex.

Market Penetration and Incentives:

It should be noted that the incremental cost of the PHEV over a conventional gasoline automatic car at 100,000 units is a function of the AER since the incremental costs is dominated by the costs of batteries. The maximum range considered to be practical and within the range of acceptable consumer reach is 60 miles. This is reasonable since the average vehicle in the US travels 40 miles per day and about 15,000 miles a year.

The AER of a HEV or PHEV can be a minimum of 10 miles to 60 miles. This range of AER is considered to be practical for the average vehicle user. This range will save gasoline depending on AER. The graphs show that the longer the AER the greater the gasoline displacement with electricity. It is assumed that driver of these vehicles will plug them in to use electricity because they can travel 4 times farther for the same dollar cost. Or using electricity to power the car is 1/4 the cost of gasoline at $3/gallon. Thus, the driver has an economic incentive to plug this car in and use electric energy to displace as much gasoline as he can. This incentive rises as the cost of gasoline goes up.

With this simple cost driver for the PHEV, the subsidy required of the government is relatively small if the cost projections are close. The manufacturers however, will have to make a tooling investment and pay for development costs which must be recovered in a relatively short period of time. Thus the initial cost must be higher than estimated because the volume of 100,000 PHEV's per year will not be achieved for at least 5 years for each manufacturer. This means there will have to be some dollar cost subsidy for at least this period of time as the volume of HEV and PHEV's are increased.

To meet cost parity with a conventional car or truck in the beginning, it may require as much as 30% of the base vehicle costs for a 60 mile AER PHEV until the volume gets to over 100,000 vehicles per year. At 100,000 vehicles per year the incremental cost could come down to as little as 10% for the PHEV 60. This is due to anticipated lower cost and durability of the batteries and the continued rise of gasoline cost and anticipated possible gasoline disruptions.

An added incentive for the purchase of the PHEV is that such a car or truck can be powered for daily travel by **personal** Solar and Wind generators at about 30% of the vehicle cost up front. This would give the individual users **energy independence** for the life of the solar or wind generator of about 30 years. The cost of fuel using personal solar or wind for the average car will drop from about 15 cents per mile for $3.00/gallon gasoline to 2 cents per mile for a solar array on top of his house or office. An incentive from the Government to buy solar or wind generators for powering the PHEV can bring

this combination technology to the market quickly. This concept also allows the excess energy generated to supplement the electric load of their home or office. In addition to **personal energy independence**, the US will benefit from greatly reduced petroleum and coal use.

US manufacturing capability to produce HEVand PHEV

The vehicle manufacturing capability of the US is currently greatly underutilized due to a shift in vehicle preference for more fuel efficient and reliable vehicles. The American car manufacturing companies have focused on large vehicles with the expectation that oil prices will remain stable at less than $50/ barrel. This strategy has led to low sales and plant closures.

Even when they have introduced hybrids they have chosen the wrong market, focusing on the larger vehicles and have chosen the most expensive technology. The example is the Ford Escape hybrid using Toyota/Aisin A/W technology, where the fuel economy is 35 mpg but the Toyota Prius gets 50 mpg. The Ford Escape hybrid is technically the same as the Prius but it is over 1000 lbs heavier. And it is better than the standard Escape in fuel economy by 50%.

However, the general public does not see these details as a limitation and thus misjudge the Escape as inferior technology to the Toyota and therefore the sales volume is falling short of expectations. The lesson learned here should be that the American public is comparing only raw fuel economy numbers independent of vehicle size and features. Costs of the complex hybrid systems is also high.

Thus the American manufacturing problem is in both lower cost technology and in choosing the right platform for the competition with Japan. There seems to be a movement toward selecting a better platform for a Plug-In hybrid at General Motors in a recent announcement of a 55 mpg PHEV to be in production by 2008 model year. The cost may not be competitive with Toyota since Toyota has already gone through three generations and are busy on a more advance PHEV with lower cost componenrts although no production date or configuration has been announced.

The only way the American car companies can compete on the same class vehicle is to introduce a lower cost, simpler but more sophisticated powertrain system. They all have selected a two motor-CVT system which is more expensive than the Toyota system. While they may be researching simpler one motor-CVT systems, there is no indication that such a system is being considered. In addition, the mechanical CVT for the HEV and PHEV has largely been ignored by the American Car companies because of some bad experiences with mechanical CVT's in the past. The bad experiences came from a lack of understanding of the CVT technology and the unwillingness of the American OEM's to fully adopt technology developed outside their laboratories. When this was tried the OEM's requirements were beyond what the technology could handle but the OEM's were unwilling to invest their own resources to understand the real problems and go through the development process themselves. Thus at least three plant investments

have been made at Billons of dollars and abandoned. Yet, there are numerous European and Japanese vehicles with CVT's but only the American Ford 500 is currently in production with a CVT under license and Joint Venture from ZF Transmission of Germany. Ford has not developed its' own system. Advance CVT technology and concepts are available in the USA and developed under a electric drive project for DARPA about 5 years ago, but no manufacturer has currently adopted the technology for production development.

It is the opinion of the Author that the Mechanical CVT is the critical technology needed for a low cost HEV and PHEV. Some of this technology has already been licensed to Japanese firms who have invested the research to prove and develop durability, low noise and much higher efficiency. There is much more Intellectual Property in this area available in this country that could be adopted by the American OEM's.

Conclusion

We have discussed the following issues and provided the data which shows the benefits of the HEV and PHEV technology.

1. The effectiveness of the HEV and PHEV for fuel, and emissions reduction.
2. The market—price relationship of the HEV and PHEV20 and PHEV60 relative to the conventional car or CV. Obviously, the technology must be priced to sell to the customers and to do any good for the US situation of imported oil it must be done in volume. Thus a target of 50% market penetration should be the goal. The author feels that initially a subsidy from the government is needed for industry to have the incentive to make the investment in this country. Foreign companies with long range planning and goals have already begun, thus the US will have to move quickly to catch up. The PHEV gives the American companies a chance to leap ahead of Japan in technology, but they must move quickly or they will be buying from Toyota again and lose more market share.
3. The use of the PHEV advanced system to move immediately toward oil independence by combining vehicle electric energy use with direct small privately owned renewable energy systems such as Solar and Wind becomes possible with the PHEV. This adds value to the concept and people have not yet fully become aware of this possibility.
4. The manufacturing capability of the American auto companies and industry is available to adopt the PHEV technology TODAY but the will to make the investment in R&D is not there even though their market share continues to erode. Thus public government support is needed.
5. Further education of the public is needed to create the demand for the PHEV. Features such as a stable ¼ cost of energy using electricity for transportation instead of the fluctuating cost of gasoline, and the possibility of personal energy independence needs to be in the forefront of the American public to create the demand.
6. The penetration of the PHEV concept into our transportation fleet and the effect on oil imports is presented. It must be remembered that we currently replace less

than 10 percent of our fleet of vehicles a year and unless earlier retirement of vehicles is encouraged, we can at best begin fleet replacement about 2% a year. Meaning a minimum of 5 years to get 10% penetration.

7. We would have the most impact on oil reduction if the vehicles sold to the public were PHEV40 to PHEV60 type. The current industry thoughts are PHEV10 to PHEV20.
8. Congress needs to set incentives to encourage the PHEV40 to PHEV 60 for initial introduction for the fastest response to the issues of imported oil, Global Warming, and energy independence/security.

Energy independence with the PHEV40 or the PHEV60 can be achieve by one individual at a time but lead to a much more affluent society because the cost of energy can be reduced to virtually zero with an enhanced and advanced life style for the American People.

I will be happy to entertain further questions on the issues of producing the PHEV for the introduction to the American Market.

America needs to take the lead to show the world we can reduce our oil consumption and respond to the Global Warming threat with immediate action.

I will be happy to answer further questions about the technology and how best to move our car companies toward the PHEV and begin the reduction of our oil addiction.