Advanced Batteries for Electric-Drive Vehicles

A Technology and Cost-Effectiveness Assessment for Battery Electric, Power Assist Hybrid Electric, and Plug-in Hybrid Electric Vehicles

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EXECUTIVE SUMMARY

Introduction

Advanced batteries are an integral component of all battery electric vehicles (BEVs), power assist hybrid electric vehicles (HEV 0s – hybrids without electric driving range), plug-in-hybrids (PHEVs) and fuel cells vehicles (FCVs). In 2000 a panel of battery technical advisory (BTAP) experts reported on near-term NiMH batteries for BEVs with about 600 to 1200 cycles based on deep cycling between 100% and 0% state of charge (SOC). The California Air Resources Board (ARB) staff estimated this would result in a near-term BEV capable of lasting only 6-years, 75,000 miles before a costly battery replacement was required, but that a 10-year, 100,000-mile BEV would eventually be possible. Almost three years later as a result of extensive studies conducted by the Electric Power Research Institute (EPRI), there is strong evidence to suggest that NiMH batteries for HEV 0s, PHEVs, BEVs and FCVs have improved significantly to the point that they are delivering longer life, better performance and are more durable than once thought. This study assesses the state of advanced battery technology for electric-drive vehicles (EDV) and presents one of the first life cycle cost analyses for vehicles with NiMH batteries.

Study Results

1. **Greater Battery Cycle Life Delivered Today:** This study concludes that NiMH batteries from top manufacturers today appear to exceed projected cycle life and durability expectations. For example 5-year old Toyota RAV 4 EVs, in real world driving, have traveled over 100,000 miles on the original NiMH battery with no appreciable degradation in battery performance or vehicle range. These vehicles are projected to last for 130,000 to 150,000 miles. These results are encouraging considering that the earlier generation NiMH batteries in these vehicles do not have the positive electrode additives to improve high temperature charge acceptance (a key breakthrough reported by the BTAP 2000). In addition, life cycle laboratory bench tests of Saft NiMH batteries between 80% and 20% SOC demonstrated 2,841 to 2,922 cycles. Battery test data presented by Ford Motor Co. at the Advanced Automotive Battery Conference show considerably more than 2000 cycles between 100% and 20% SOC and also confirmed that shallower discharge cycling between 80% and 20% SOC results in even greater cycle life. These tests clearly exceed the near-term 600 to 1200 cycle projections by BTAP 2000 experts.

2. **One Battery Pack per Vehicle, Not Two as Originally Projected:** Greater battery cycle life means it is highly probable that NiMH batteries can meet 130,000 – 150,000 lifetime mileage for HEV 0s, PHEVs with 40 to 60 miles of electric driving range, and full function BEVs. It is likely that PHEVs with 20 miles of electric range (PHEV 20) can meet this target, but further testing is needed.

    - BEVs can travel 130,000-150,000 ZEV miles on the original battery pack.

- PHEV 20s can reach 150,000 total miles on original pack with 33,000 – 66,000 miles in BEV mode using off-board electricity from the grid and additional HEV mode miles.
- PHEV 40s can reach 150,000 total miles on original pack with up to 100,000 miles in BEV mode using off-board electricity and additional HEV mode miles.

3. Electric-Drive Vehicles Can Achieve Life Cycle Cost Parity With Conventional Gasoline Vehicles: While the upfront estimated price to consumer are likely higher, depending on automaker pricing strategies, substantial fuel and maintenance savings can eventually compensate for a higher upfront cost. This study updated the ARB life cycle cost model from 2000, using ARB assumptions of $1.75 per gallon gasoline and 8% discount rates combined with the improved battery cycle life information referenced above and refined assumptions for motor, controller, engine, battery, maintenance, and fuel economy costs. A minimum production volume assumption of 100,000 per year for hybrid system components was used. This study presents one of the first life cycle cost analysis of today's advanced batteries. The key conclusions of the life cycle cost part of EPRI's study (in the 10-year 150,000-mile HEV scenario) are:

- HEV 0s can reach life cycle cost parity with their conventional vehicle (CV) counterparts. HEV 0 batteries in medium volume production of about 100,000 per year will cost about $400 per kWh and this is near the bottom of their cost curve. At this price the net present value (NPV) of a mid-size HEV 0 is $500 less than its gasoline counterpart, and a full-size SUV HEV 0 is $86 less than its gasoline counterpart. This is without the carmaker passing on to the consumer its approximately $500 per HEV 0 benefits from CAFE compliance, depending on the carmaker's CAFE compliance situation.

- PHEV 20s can reach life cycle cost parity with their CV counterparts. PHEV 20 batteries in medium-volume production of about 100,000 per year will cost about $320 per kWh for a mid-size car and about $350/kWh for the full-size SUV. At this price the net present value (NPV) of a mid-size PHEV 20 is $1,207 lower than the gasoline counterpart. The full-size SUV PHEV 20 is $1,137 lower than the gasoline counterpart. This is without the carmaker passing on to the consumer its approximately $1000 per PHEV 20 benefit from CAFE compliance depending on the carmaker's CAFE compliance situation.

- City EVs can reach life cycle cost parity with their CV counterparts in a 10-year, 110,000-mile scenario for urban driving. The study used a micro car battery EV (such as a Kamkorp-TH!NK Nordic, or E-motion vehicle) with 40-mile range (BEV 40) and assumed it used PHEV 20 batteries. When using PHEV 20 batteries in 100,000 per year production, the net present value of a BEV 40 is $423 less than the gasoline counterpart (CV). This is without the carmaker passing on to the consumer its approximately $2000 per BEV 40 benefits from CAFE compliance depending on the carmaker's CAFE compliance situation.

4. Near-term Commercialization of Power Assist HEVs (HEV 0) Strengthens the Business Case for BEVs and PHEVs: With so many automakers such as Toyota, Honda, Nissan and GM making HEV announcements, or already in the market, power assist HEV market penetration is expected to exceed one million units worldwide by 2010. Volume production of HEV 0s (which use "power" batteries) will drive down the cost of advanced componentry, primarily high-power electric drive motors, motor controllers (inverters), and other electrical hardware. There appears to be a worldwide business case for HEV 0s although temporary public sector assistance is likely needed to help reach higher volume production. The availability of lower cost EDV components will have a significant impact on the life- cycle cost of BEVs and PHEVs reducing their upfront cost to the consumer. A critical remaining challenge is to lower the cost of high-energy advanced batteries by increasing the production volumes of PHEVs and BEVs. A key conclusion of both the original EPRI HEVWG report and this study is that commercialization of plug-in hybrids is a viable path to achieving the necessary production demand for higher capacity, "energy" batteries required by BEVs and PHEVs.

5. **At Modest Production Volumes, PHEVs Can Achieve Life Cycle Cost Parity with CVs and HEV 0s:** In the past, $150 per kWh was the often-stated goal for "energy" batteries, based on USABC estimates in the early 1990s. This latest EPRI study concludes that life cycle cost parity later this decade is possible within a range of $380 to $471 per kWh if, as expected, HEV 0s bring down the cost of electric motors and controllers. Battery experts indicate that this cost range is attainable by a battery manufacturer at production volumes between 48,000 to 150,000 PHEV 20 battery packs per year. The EPRI – HEV Working Group collaborative market assessment concluded that there is substantial market potential for PHEVs (and for HEV 0s) even with higher upfront costs.

6. **HEV 0s, PHEV 20s, and BEV 40s Can Cost-effectively Reduce Smog-forming Emissions, Greenhouse Gases and Petroleum Use:** When product life cycle cost parity is reached, society is achieving emission and petroleum reduction for essentially zero cost. In technical terms, the cost-effectiveness of reducing pollution, petroluem consumption and global warming gases is $0 per ton of pollution removed. In almost all the scenarios analyzed, HEV 0, PHEV 20 and BEV 40 products reach life cycle cost parity after several years of fuel and maintenance savings, thereby securing pollution reductions for $0 per ton.

Summary

This new EPRI battery study builds on two previous studies conducted by the EPRI Hybrid Electric Vehicle Working Group (HEVWG), a partnership of automakers, utilities, ARB, South Coast AQMD, Department of Energy, and academic researchers.

This study concludes that NiMH batteries from the top manufacturers appear to significantly exceed previous projections by ARB staff for cycle life and durability. It is highly probable that NiMH batteries can be designed, using current technologies, to meet the vehicle lifetime requirements of full-function battery EVs, city EVs, and plug-in HEVs. This significant development could mean that only one battery pack per vehicle is required for the life of that vehicle, not two as previously projected.

The cost of advanced batteries for HEV 0s, PHEVs, and BEVs is highly dependent on the establishment of a stable market situation, a predictable regulatory environment, and consistent production volumes that encourage capital investment in production capacity and line automation.

HEV 0s, PHEV 20s, and BEV 40s analyzed in this study can cost-effectively reduce smog-forming gases, greenhouse gases and petroleum consumption. In almost all scenarios analyzed, HEV 0, PHEV 20 and BEV 40 products reach life cycle cost parity, securing pollution reductions for $0 per ton.

HEV 0s in volume will help drive down the cost of motors and controllers that will be used in BEVs, PHEVs, and ultimately fuel cells. However it is the commercialization of the PHEV that holds the key to addressing the one remaining barrier to battery powered vehicles – the cost of the "energy" battery.

1
DETAILED SUMMARY AND INTRODUCTION

Introduction

Recent information on battery progress over the last three years is showing a significant increase in expected battery life. In addition, recent announcements by vehicle manufacturers regarding their plans to mass produce hybrid electric vehicles (HEVs) will quickly drive down the costs of electric-drive components (drive motors, power inverters, etc.). With this new information, it is possible for power assist hybrid electric vehicles (HEV 0s), plug-in HEVs with 20 mile daily all electric range (PHEV 20s), and pure EVs with small battery packs[1] to meet life cycle cost parity with conventional vehicles at higher battery module prices than previously thought. The cents per mile costs of batteries for these vehicles can exceed the de-facto USABC[2] life cycle costs goals.

This study presents one of the first life cycle cost analysis for HEVs and battery electric vehicles (BEVs) with nickel metal hydride (NiMH) batteries. This study assesses the state of advanced battery technology for electric-drive vehicles (EDV) including battery electric vehicles, power assist and plug-in hybrid electric vehicles, and fuel cell vehicles. It provides evidence that significant progress has been made in developing battery technologies that are capable of effectively powering battery electric vehicles and plug-in hybrid electric vehicles. Availability of affordable, advanced battery technology is a crucial challenge to the growth of the EDV market.

This study was conducted by EPRI with considerable input from respected experts in this field. This study expands on the Hybrid Electric Vehicle Working Group (HEVWG)[3] work detailed in two key reports [R-1, R-6].

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[1] Pure battery EVs can vary from "micro cars" with federal safety certification, called City EVs, up to full-function EVs, which are federal safety certified vehicles that can travel on freeways and highways. HEVs are full-function electric drive vehicles (EDVs) that include many designs. HEV 0s in this study are "full" hybrids using a parallel design that deliver about 50% fuel economy improvement, but do not use off-board electricity. PHEV 20s in this study use a larger battery and electric motor than an HEV 0, also use a parallel design, and have two driving modes – an HEV mode like the HEV 0 and a BEV mode. PHEVs use off-board electricity (e.g. nightly charging at home) to recharge their miles in BEV mode. Fuel cell vehicles in this study are hybridized designs in order for the fuel cell vehicle to provide instantaneous power for acceleration, provide energy when idling at a stop, and to recover regenerative braking energy when coasting, traveling downhill or braking. Hybridized FCVs can either based on the HEV 0 or PHEV concepts. See report glossary for more definitions on the types of EDVs in this report.

[2] United States Advanced Battery Consortium

[3] The HEVWG consisted of representatives of the utility and automotive industries, along with those of the U.S. Department of Energy (DOE), the California Air Resources Board (ARB), South Coast Air Quality Management District and academic researchers. The work involved determine the cost, fuel economy, consumer acceptance and policy implications of hybrid electric and plug-in hybrid electric vehicles for mid-size, compact and sport

Two and half years ago the Air Resources Board (ARB) and staff were told by their panel of experts to expect NiMH batteries for battery EVs in the near-term with about 600 to 1200 cycles between 100% and 0% SOC [R-2]. The ARB staff estimated this would result in a 6-year, 75,000-mile vehicle in the near term [R-5] before a costly battery replacement was required, but that a 10-year, 100,000-mile BEV would eventually be possible.

This section summarizes the report methodology and major conclusions. Section 2 examines the prospects for PHEV batteries (NiMH, lithium ion and other advanced batteries). Section 3 examines battery cost and life. Sections 4 and 5 of this study examine the life cycle costs of PHEV 20s, HEV 0s and city EVs compared with their gasoline counterparts. Section 6 examines how these results can impact policy development, such as cost-effectiveness of pollution reductions. Appendixes A through C support Sections 4 and 5.

Battery Cost and Life Conclusions

A key conclusion of this study is that NiMH batteries from the top manufacturers appear to be exceeding projected cycle life and durability expectations. It is highly probable that NiMH batteries can be designed, using current technologies, to meet the 130,000 –150,000-mile vehicle lifetime requirements of full-function battery EVs with 40 to 60 miles of EV range, city EVs[4], and plug-in HEVs with 20 miles of EV range[5].

Real world testing has confirmed NiMH battery lifetimes exceeding 5 years and 100,000 miles on several vehicles. Specifically, Toyota RAV4-EVs are successfully operating for more than 100,000 miles on the original NiMH battery, and are projected to last for 130,000 to 150,000 miles. In addition, life-cycle laboratory bench tests of Saft NiMH batteries have demonstrated 2,841 to 2,922 cycles when cycled between 80% and 20% battery state of charge (SOC). This exceeds the 1750 deep cycles when cycled between 100% and 20% SOC estimated by the HEVWG two years earlier [R-1]. Current data from top battery manufacturers show thatfor NiMH batteries will exceed 2000 deep cycles when used in PHEVs and BEVs.[6]

This new information on NiMH battery life indicates that the cost-effectiveness of many types of electric-drive vehicles has improved and can lead to life cycle cost parity of BEVs and PHEVs with conventional vehicles. Clearly, real world testing is needed to validate this very promising laboratory information. Table 1-1 contrasts expectations 2.5 years ago for NiMH batteries with the new estimates based on the five sources above.[7] The significant implication of this combined

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utility vehicles. See http://www.epri.com/corporate/discover_epri/news/2001releases/010905_hybrid.html in order to obtain the HEVWG study and press release [R-1] at no cost.

[4] City EVs using city streets have lower lifetime mile requirements (e.g. 87,000-mile scenario by ARB)

[5] This statement is for PHEV 20s that do not limit lifetime EV miles to extend battery pack life. Further testing is needed for these vehicles. PHEV 20s that employ a control strategy to extend battery life are more likely to extend battery life, but will have reduced benefits due to a reduction in lifetime EV mileage.

[6] Section 2

[7] Table 1-1 assumes NiMH from top manufacturers, design data from the HEVWG studies [R-1, R-6], a real world driving factor of 0.85, and this study's estimates for a BEV 40 and RAV 4 EV with improved nickel electrode NiMH batteries and improved battery control systems

evidence from well-respected experts is that only one battery pack per vehicle will be required for the life of higher mileage vehicles -- not two as previously projected.

Table 1-1
Estimated Miles on Original NiMH pack for Various Electric Drive Vehicles

Vehicle	BEV miles[a] from off-board electricity on original pack	Additional HEV engine miles[a] on original pack	Total miles[a] on original pack	Battery size (kWh)
Mid-size PHEV 20	33,000 (with 80% cycles) – 66,000 (with 60% cycles)	About 100,000	130,000 – 150,000	5.9 – 8.0
Mid-size PHEV 60	100,000 (with 80% cycles) – 130,000 (with 70% cycles)	About 100,000	200,000 – 230,000	17.9 to 20.5
BEV 40 city car (micro car)	75,000(with 80% cycles) – 100,000[b] (with 70% cycles)	None	88,000 – 110,000	9.1
Mid size BEV[c]	130,000 – 150,000[d]	None	About 150,000	27.0
Mid-size HEV 0	None	130,000 – 150,000[e]	130,000 – 150,000	2.9

[a] Real world miles using a discount factor of 0.85.

[b] 70% deep cycles (e.g. from 90% to 20% state of charge)

[c] For example Toyota RAV4 EV with 80-95 mile range per charge using 80% cycles.

[d] ARB staff estimated only 74,300 miles on the first NiMH pack for a near-term BEV in their August 2000 report [R-5] Vehicle 3 in ARB life-cycle cost model

[e] Compared to [R-5] where Vehicle 22's first battery lasted 117,000 miles

Life Cycle Cost Methodology and Conclusions for HEV 0s, PHEV 20s and BEV 40s

The majority of this study examines NiMH batteries that were the focus of the two major HEVWG reports. These earlier studies found that PHEV 20 and PHEV 60 vehicles with NiMH batteries have substantial market potential (as high as 50%), can take advantage of the ubiquitous 120 V electricity infrastructure, can be designed to meet consumers' performance expectations, and can deliver substantial reductions in CO_2 emissions, petroleum use, and smog-forming gases (NO_x and ROG) compared to very clean (SULEV[8]) gasoline engine counterparts.

This study uses a version of the life-cycle cost model (vehicle, fuel and maintenance) developed by ARB in 2000 [R-5].[9] Based on the improved battery cycle life information in Sections 2 and

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[8] SULEV refers to ARB's Super Ultra Low Emission Vehicle emissions standard for tailpipe and evaporative emissions.

[9] ARB's key assumptions of $1.75 per gallon gasoline, $0.05 per kWh off-peak electricity, 3% inflation, 8% discount rate, and 10-year 117,000-mile vehicle life we used.

3, a 10-year / 150,000-mile scenario is also examined for the HEV 0s and PHEV 20s as well as a high mileage city EV scenario. The ARB model has been updated with more conservative and detailed assumptions for motor, controller, engine, battery and other component costs using HEVWG data. In addition more conservative and detailed assumptions are used for maintenance, fuel economy and secondary use of batteries. A key assumption is that mass production of HEV 0s[10] will reduce motor and controller costs for PHEVs and BEVs to those estimated by the HEVWG at production levels of 100,000 units per year [R-1].

The key conclusions of the life cycle cost part of the study (in the high mileage scenario) are:

- HEV 0s can reach life cycle cost parity with their conventional vehicle counterparts. HEV 0 batteries in medium volume production of about 100,000 per year will cost about $400 per kWh and this is near the bottom of their cost curve. At this price the net present value of life cycle costs for a mid-size HEV 0 over a 150,000 mile/10 year life is $500 less than its gasoline counterpart. The full-size SUV HEV 0 life cycle costs are $86 less than its gasoline counterpart (CV or conventional vehicle) over the same lifetime. This is conservative as many carmakers could pass on CAFE compliance benefits for an HEV 0 worth approximately $500, or use of pricing methods often used to gain market share, improve image or capture new types of buyers [R-9, R-10].

- PHEV 20s can reach life cycle cost parity with their conventional vehicle counterparts. PHEV 20 batteries in medium-volume production of about 100,000 per year will cost about $320 per kWh for a mid-size car and about $350/kWh for the full-size SUV. As shown in Figure 1-1 at this battery module price, the net present value of life cycle costs over a 150,000/10 year lifetime for a mid-size PHEV 20 is $1,207 lower than the CV. The full-size SUV PHEV 20 in Figure 1-2 is $1,137 lower than the CV over the same lifetime. This is conservative as many carmakers could pass on CAFE compliance benefits for PHEV 20s worth approximately $1000 per vehicle, or use pricing methods to gain market share, improve image or capture new types of buyers [R-9, R-10]. The vehicle retail price equivalent (RPE) in Figures 1-1 and 1-2 includes dealer and manufacturer profits, which in the case of the SUVs is substantial.

- City EVs can reach life cycle cost parity with their conventional vehicle counterparts. This study used a micro car battery EV (such as a Kamkorp-Think Nordic, or E-motion vehicle) with 40-mile range (BEV 40) and assumed it used PHEV 20 batteries. When using PHEV 20 batteries in 100,000-per-year production, the net present value of life cycle costs for a BEV 40 is $421 less than the CV version. This is without the carmaker passing on to the consumer its approximately $2000 per BEV 40 benefits from CAFE compliance.

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[10] Based on automaker product announcements for millions of HEVs by the end of the decade.

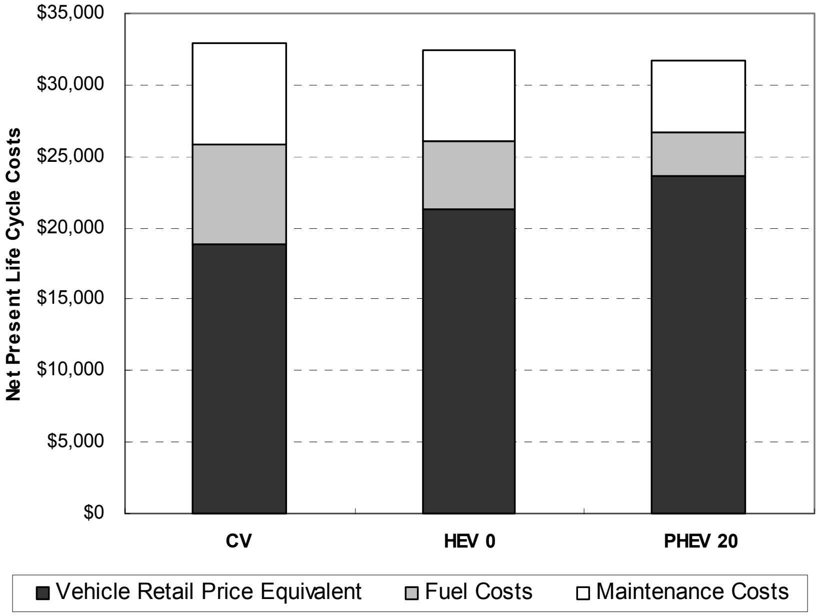

Figure 1-1
Net Present Value of Full Life Cycle costs for Mid-size Sedans

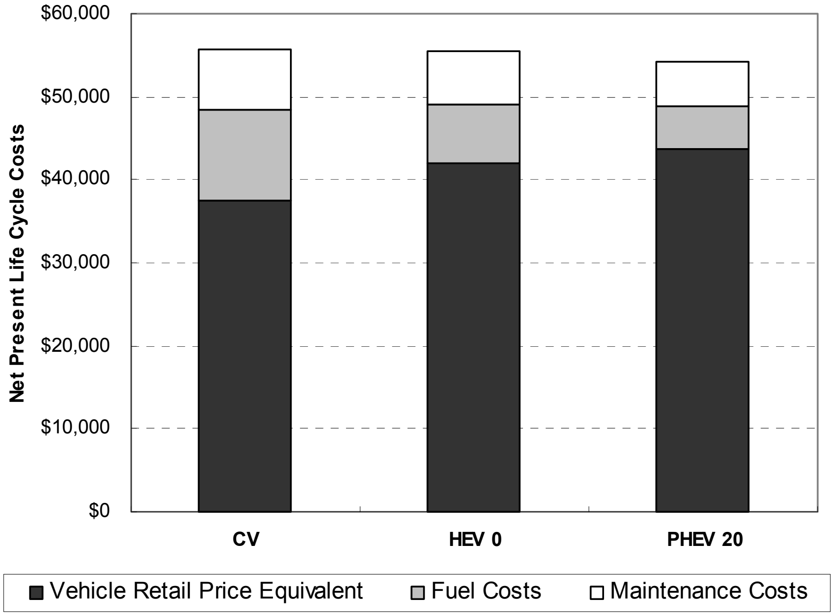

Figure 1-2
Net Present Value of Full Life Cycle costs for SUVs

In addition, it is possible that PHEV owners could receive payments by the end of the decade that would substantially reduce the cost of the battery. The payments would be for contracts with electrical grid operators, e.g. the California Independent System Operator (Cal ISO), to provide services that help stabilize the grid (regulation services or spinning reserve standby) and do not significantly reduce battery lifetime energy. EPRI, Cal ISO, and academic researchers are investigating this concept in depth.

With so many automakers such as Toyota, Honda, Nissan, and GM making HEV announcements, or already in the market, HEVs (that use "power" batteries) are expected to far exceed one million worldwide by 2010.[11] This will cause the price of motors and controllers for electric drive vehicles to fall to near the bottom of their cost / volume curves by the end of this decade.[12] Based on this, there appears to be a worldwide business case for HEV 0s, although public sector assistance is likely needed in the early years in order to help reach this volume production. These low price motors and controllers and other EDV components will have a very significant impact on the life cycle cost of PHEVs. The largest remaining challenge will be to bring down the cost of plug-in hybrid electric vehicle "energy" batteries.

Figures 1-3 and 1-4 show how a PHEV 20, using relatively low cost motors and controllers from medium-volume HEV 0s, can use relatively expensive, low volume production PHEV 20 "energy" batteries and still reach life cycle cost parity with the CV and HEV 0. Specifically, Figures 1-3 and 1-4 show that PHEV "energy" batteries do not need to obtain the often stated goals of $150 per kWh or even the $235/kWh as stated in the BTAP 2000 report [R-2]. These Figures show the net present value of the fuel and maintenance costs plus the vehicle retail price equivalents[13] (RPEs) for the PHEV 20, HEV 0, and CV versus the battery module cost ($/kWh). With mass production, the battery module cost and the NPV of the life cycle costs decrease. PHEV 20 mid-size cars reach life cycle cost parity with the CV at $471/kWh and the PHEV 20 full-size SUVs reach life cycle cost parity with the CV at $455/kWh. In other words, PHEV 20s can reach life cycle cost parity with CVs at relatively low-volume productions of about 50,000 PHEV 20s per year, and at slightly higher production, reach life cycle cost parity with HEV 0s.[14]

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[11] For example, Toyota has announced plans to increase the number of HEV models to more than 10 by 2006 from its current three. Toyota's goal is 300,000 HEVs by middle of this decade increasing to one million per year by 2010. An auto analyst at Morgan Stanley predicted HEV sales in the US next decade at 10 to 15% of the 17 million annual sales. An analyst at Merrill Lynch pointed out that because Japanese automakers view HEVs as the core technology, domestic automakers have to respond. [11] GM, in fact, has announced plans for 5 new HEVs by 2007 with 1 million GM HEVs expected by end of the decade. See section 4 for details and citations

[12] Or at least the medium-volume 100,000-per-year production levels assumed in this study.

[13] Retail price equivalent in this study uses the DOE Argonne National Laboratory method of estimating the retail price based on direct costs and estimates of indirect costs as well as dealer and manufacturer profits.

[14] The two declining lines in Figures 1-3 and 1-4 stop at the left side of the figures, and this point where they stop equals the bulleted conclusions discussed earlier and equals the grand total bars in Figures 1-1 and 1-2. In other words, this point is where PHEV 20s and HEV 0s battery production costs reach 100,000 per year volumes.

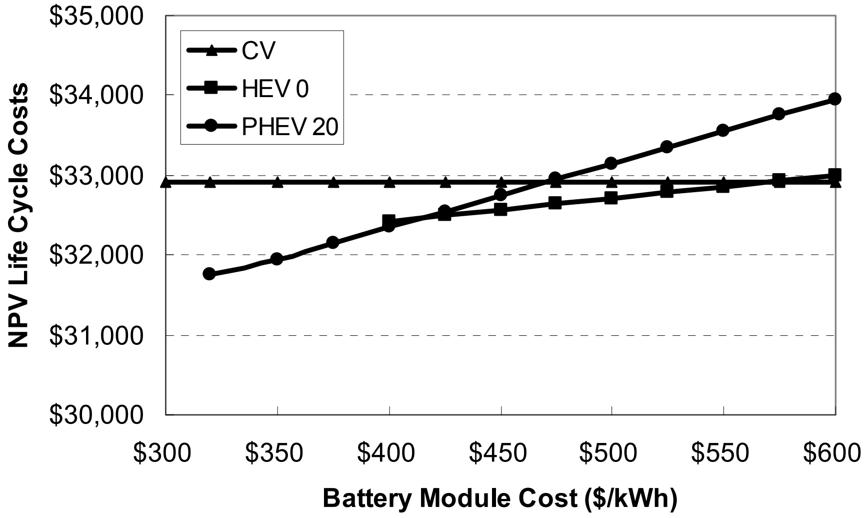

Figure 1-3
Life cycle cost versus battery module cost for mid-size car (10-year, 150,000 mile case)

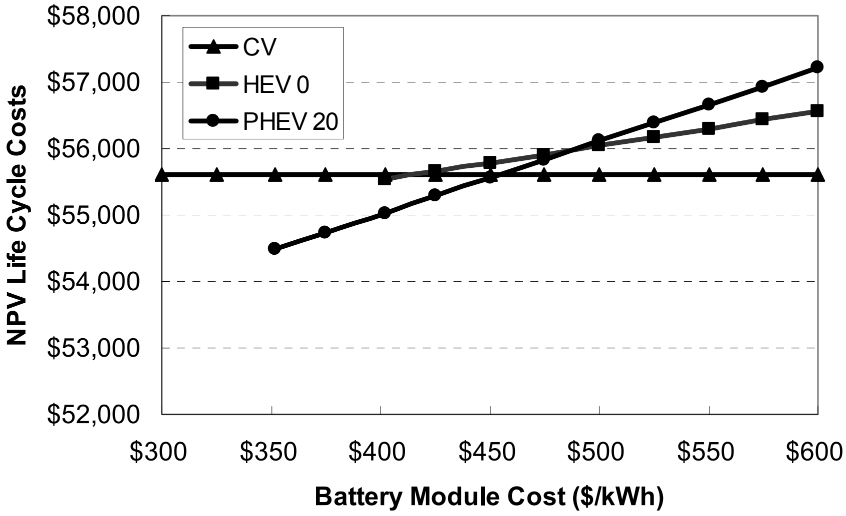

Figure 1-4
Life cycle cost versus battery module cost for SUV (10-year – 150,000-mile case)

The above conclusions together with the aggressive announcements to commercialize HEV 0s demonstrate a viable commercialization path. HEV 0s and PHEV 20s can be commercialized together. HEV 0s will likely be responsible for bringing down the price of motors and controllers. However, it is commercialization of PHEVs that holds the key to addressing the one remaining major barrier to PHEVs and BEVs – the cost of the "energy" battery. PHEVs using

NiMH “energy” batteries appear to have the market potential and business case to bring down the price of “energy” NiMH batteries, and then these batteries can also be used in City EVs. Note that PHEV 20s and BEVs can’t use the “power” batteries used in HEV 0s.

When the USABC goals for $150/kWh battery prices are translated into cents per mile goals, PHEV 20s can more than meet them. The USABC goal of $150 per kWh combined with a goal of a 150,000 mile life translates into a goal of 2.24 to 3.12 cents per mile, assuming 0.25 to 0.33 kWh/mile vehicle efficiency and this study’s assumption of 2000 80% DOD cycles. By contrast, the mid-size PHEV 20 with a 5.88 kWh battery pack at its estimated minimum cost of $320/kWh costs only 1.25 cents per mile. These life cycle cost findings also lend support to a business case for battery leasing (own the car, but lease or rent the battery) in order to turn batteries into an operating cost as opposed to an upfront incremental cost. In a trial program in Europe, battery leasing has substantially increased the sales of BEVs compared with the earlier efforts to sell or lease BEVs.

Willingness of Consumer to Pay More for HEVs

These life cycle cost conclusions beg the question, “Are consumers willing to pay more for HEV 0s and PHEV 20s than their CV counterparts?” The HEVWG collaborative research with automakers [R-1, R-6] conclude that consumers are willing to pay about $2250 more for a mid-size car HEV 0, about $3000 more for a full-size SUV HEV 0, about $3600-$4000 more for a mid-size PHEV 20, and about $5500 more for a full-size SUV PHEV 20.[15] The reason for interest in HEVs apparently is not just the fuel economy benefits, but, in the case of the PHEV 20s, at least nine additional benefits [R-1].

- Less maintenance (due to the electric componentry and EV miles)
- Substantially fewer trips to the gas station,
- The convenience of having a full battery every morning
- Reductions in vehicle air pollution, petroleum use, and global warming gases
- Less noise/vibration,
- Improved acceleration,
- Convenience features such pre-heat/pre-cool with the engine off or use of 120 V appliances (tools, TVs, refrigerators, lights, etc) from the vehicle electrical system,
- Better handling due to balanced weight distribution, and

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[15] These types of studies probably overestimate the willingness to pay and recoup with operating cost savings. Public sector assistance is likely needed in the early years until volume production is attained.

- Better handling and other benefits due to lower center of gravity

Policy Implications

HEV 0s, PHEV 20s, and BEV 40s analyzed in this study can cost-effectively reduce smog-forming gases, greenhouse gases, and petroleum. When consumer life cycle cost parity is reached, society achieves these important benefits at no additional cost.[16] In almost all the scenarios analyzed, HEV 0, PHEV 20 and BEV 40 drivers reach life cycle cost parity, thereby securing pollution reductions at no additional cost to the consumer. Life cycle cost parity, however, could take many years to achieve unless financial strategies such selling the car and leasing the batteries are used. Pricing methods that pass on carmaker benefits such as CAFE compliance, or if gasoline price remain above the study's $1.75 per gallon assumption can make life cycle cost parity occur much sooner.

Other Conclusions

The cost of advanced batteries for HEV 0s, PHEVs, and BEVs is highly dependent on production volume and a consistent market situation that encourages capital investment in production capacity and line automation. In the case of electric vehicle battery modules, the anticipated production volumes did not occur; therefore these "energy" battery products have not yet seen the resulting decreases in cost. Future increases in production volume and accompanying production contracts to battery vendors for electric vehicle battery modules will create downward pressure on EV battery prices with contracts to battery vendors for PHEV battery modules demonstrating similar downward pressure on PHEV battery prices. The cost of advanced batteries for HEV 0s, PHEVs, and BEVs is highly dependent on the establishment of a stable market situation, a predictable regulatory environment, and consistent production volumes that encourage capital investment in production capacity and line automation.

The stable market, regulatory situation over the last two years has lead to considerable investment in both "power" batteries used in HEV 0s as well as a surprising level of investment in two "energy" batteries not discussed much in this study. There are at least six developers of NiMH batteries. Several new NiMH battery-manufacturing plants (with hundreds of millions of dollars investment) with "power" battery production lines have opened in the last two years or are about to open (e.g. Panasonic, Saft, Chevron-Texaco-Ovonics, Sanyo). They can relatively easily add lines for the production of PHEV NiMH "energy" batteries that can be used in either PHEVs or BEVs. However, unfortunately, regulatory confusion concerning the California Zero Emission Vehicle Program has contributed to a loss of momentum in the development and production of NiMH high specific energy batteries for BEVs, PHEVs, and fuel cell EVs.

Nevertheless, two "energy" battery-manufacturing facilities have opened in the last two years. In 2002 MES-DEA opened a $66 million battery factory for sodium nickel chloride (ZEBRA) batteries used in BEVs, and Avestor opened a $56 million plant for "energy" batteries to be used

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[16] In technical terms, the cost-effectiveness of reducing pollution, petroluem consumption and global warming gases is $0/ton of pollution removed.

in telecommunication applications with announced plans for a larger version of this battery to be used in city EVs. See the full report for more details.

R
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GLOSSARY

A	Ampere(s)
AE	All-electric
AER	All-electric range, i.e., the nominal range of a plug-in HEV when operating in electric-only mode
CV	Conventional Vehicle
DC	Direct current
DOD	Depth-of-discharge
EPRI	Electric Power Research Institute
EV	Electric vehicle
HEV	Hybrid Electric Vehicle
HEVWG	Hybrid Electric Vehicle Working Group
HEV 0	A parallel hybrid with no all-electric range
HEV 20	A parallel hybrid with "plug-in" capability (that is, capability for battery recharging from an off-board source of electricity) and a battery providing about 20 miles of all-electric range
HEV 60	A parallel hybrid with plug-in capability and a larger battery providing about 60 miles of all-electric range
kg	Kilograms
kW	Kilowatt(s)
kWh	Kilowatt hour(s)
kWh/mi	Kilowatt hours per mile

NiMH	Nickel metal hydride
PNGV	Partnership for a New Generation of Vehicles
SOC	State of charge
V	Volt(s)
W	Watt(s)
Wh	Watt-hour(s)
ZEV	Zero Emission Vehicle