Advanced Batteries for Electric-Drive Vehicles

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

Technical Report

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EPRI Project Manager
M. Duvall

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute

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Kalhammer Electrochemical and Energy Technology

Sacramento Municipal Utility District

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CITATIONS

This report was prepared by

Electric Power Research Institute
3412 Hillview Ave.
Palo Alto, CA 94304

Principal Investigator
M. Duvall

ICF Consulting
P.O. Box 1678
Aptos, California 95001

Principal Investigator
L. Browning

Kalhammer Electrochemical and Energy
Technology
424 Barnegat Lane
Redwood Shores, CA 94065

Principal Investigator
F. Kalhammer

Sacramento Municipal Utility District
P.O. Box 15830
Sacramento, CA 95852-1830

Principal Investigator
W. Warf

Southern California Edison
2244 Walnut Grove Ave
Rosemead, CA 91770-3714

Principal Investigators
D. Taylor
M. Wehrey
N. Pinsky

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REPORT SUMMARY

Availability of affordable advanced battery technology is a crucial challenge to the growth of the electric-drive vehicle (EDV) market. This study assesses the state of advanced battery technology for EDVs, which include battery electric vehicles (BEVs), power assist hybrid electric vehicles (HEV 0s – hybrids without electric driving range), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles. The first part of this study presents assessments of current battery performance and cycle life capabilities as well as cycle life prospects and costs of batteries designed for EDV applications. The second half is a life cycle cost analysis for these applications using new information and a refined version of a California Air Resources Board cost model.

Background

This report represents a continuation of EPRI's EDV research. EPRI formed the Hybrid Electric Vehicle Working Group by bringing together representatives of the utility and automotive industries, the U.S. Department of Energy (DOE), other regulatory agencies, and university research organizations. The first study, Assessment of Current Knowledge of Hybrid Vehicle Characteristics and Impacts (EPRI report TR-113201), defined important ground rules for studying HEV technology. The second study, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options (EPRI report 1000349), focused on the key attributes of HEV performance, energy economy, fuel cycle emissions, costs, consumer acceptance, and commercialization issues for mid-sized vehicles. A follow-on report, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles (EPRI report 1006892), examined the performance, energy economy, fuel cycle emissions, costs, and consumer acceptance for compact and sports utility HEVs and their conventional counterparts.

Objective

- To assess the state of advanced battery technology for electric vehicle (EV) applications including BEVs, power assist HEVs, and PHEVs.
- To analyze the life cycle costs of these vehicles in an effort to determine the production cost targets necessary for commercial viability.

Approach

EPRI collected and analyzed data from field and laboratory tests and battery industry experts to develop this report. EPRI refined a life cycle cost model used by the California Air Resources Board in 2000 to include new data and information on the costs of electric drive vehicles.

Results

A key conclusion of this study is that nickel metal hydride (NiMH) batteries from the top manufacturers appear capable of exceeding recent cycle life and durability projections. It is now highly probable that NiMH batteries featuring state-of-the art materials and designs can meet the lifetime requirements of full-function BEVs, PHEVs with 40 to 60 miles of EV range, city EVs, and possibly even PHEVs with 20 miles of EV range (although further testing is needed to confirm this). Economic analysis shows that life cycle cost parity is possible for power assist HEV 0s, PHEV 20s, and BEV 40s (short-range city EVs) compared to their gasoline counterparts. This has important implications for decision makers looking for cost-effective ways to reduce criteria pollutants, greenhouse gas emissions, and petroleum consumption of cars and light trucks.

EPRI Perspective

This report summarizes relevant knowledge and findings concerning advanced batteries for BEV and HEV applications. It provides evidence that significant progress has been made in developing battery technologies capable of effectively powering BEVs and PHEVs.

Keywords

Nickel Metal Hydride Battery
Lithium Ion Battery
Advanced Battery
Battery Cycle Life
Battery Cost
Battery Electric Vehicle (BEV)
Plug-In Hybrid Electric Vehicle (PHEV)
Power Assist Hybrid Electric Vehicle (HEV 0)
City Electric Vehicle
Life Cycle Costs
Grid-Connected Hybrid Electric Vehicle

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 vehicles (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 it's 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 it's 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.

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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

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 that for 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

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policy implications of hybrid electric and plug-in hybrid electric vehicles for mid-size, compact and sport 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

the new estimates based on the five sources above.[7] The significant implication of this combined 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.

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[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

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

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 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 it's approximately $2000 per BEV 40 benefits from CAFE compliance.

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[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.

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

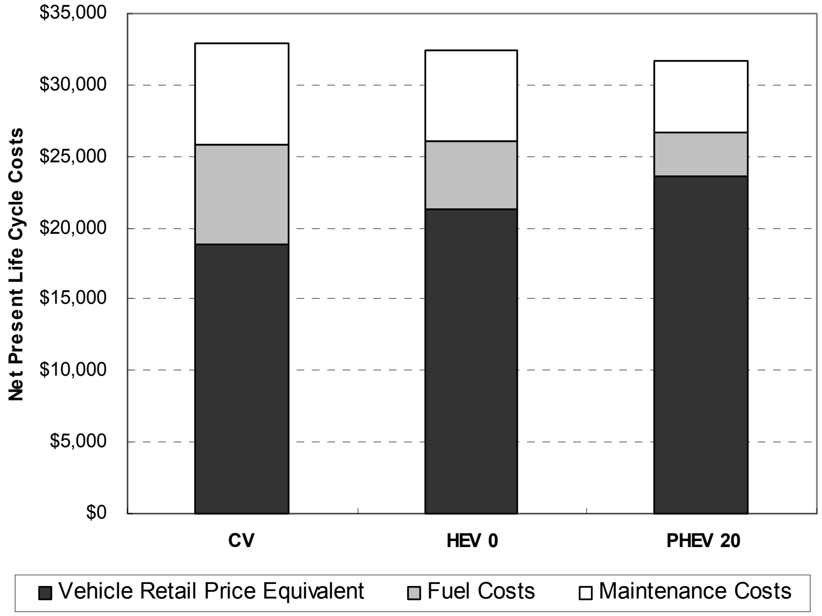

Figure 1-1
Estimated Miles on Original NiMH pack for Various Electric Drive Vehicles

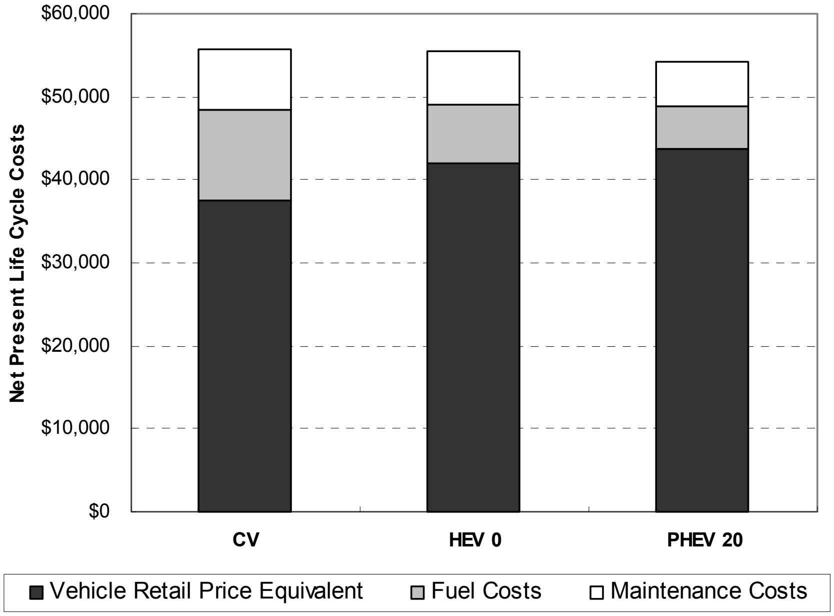

Figure 1-2
Net Present Value of Full Life Cycle costs for SUVs

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.

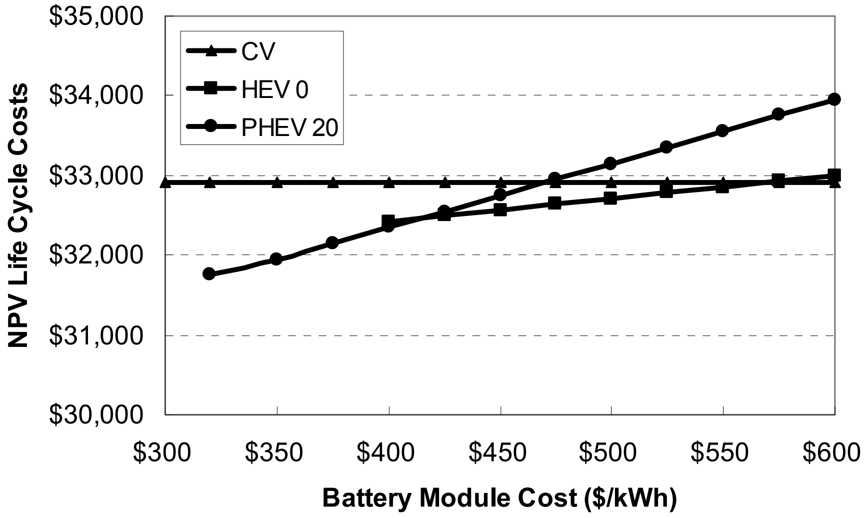

Figure 1-3
Life cycle cost versus battery module cost for mid-size car (10-year, 150,000 mile case)

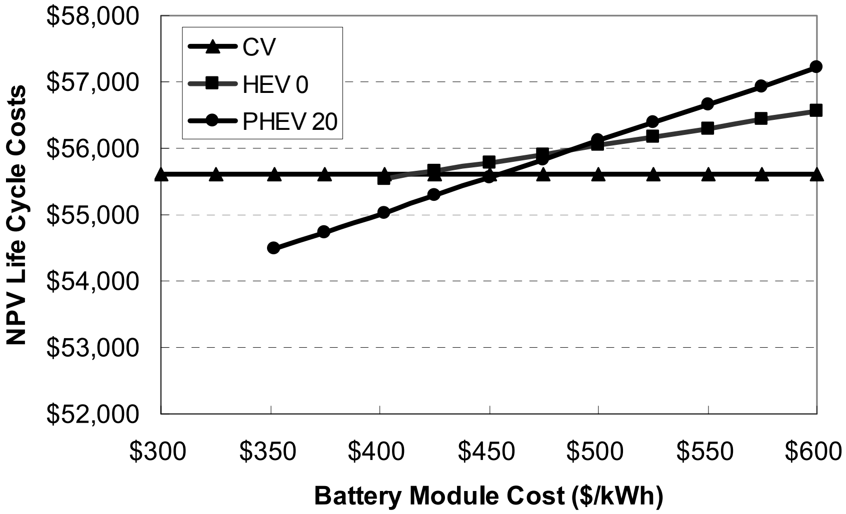

Figure 1-4
Life cycle cost versus battery module cost for SUV (10-year – 150,000-mile case)

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
- 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

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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.

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

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 in telecommunication applications with announced plans for a larger version of this battery to be used in city EVs. For additional conclusions and results see the last parts of Sections 3, 4, and 5.

2

THE PROSPECTS OF BATTERIES FOR PLUG-IN HYBRID ELECTRIC VEHICLES

Introduction

Dr. Kalhammer served as chair of the Year 1995 and 2000 California Air Resources Board Battery Technical Advisory Panels (BTAP and BTAP 2000, respectively), assessing the cost and availability of advanced batteries for electric vehicles. Dr. Kalhammer is also a member of the HEV Working Group and has provided the following review of nickel metal hydride and lithium ion battery technologies for plug-in hybrid electric vehicles.

Summary

The current status of nickel metal hydride and lithium ion batteries was reviewed recently to answer concerns about the availability of batteries that can meet the performance, cycle life and cost requirements for plug-in hybrid electric vehicles (PHEVs). The main conclusions from this review are as follows:

1. Nickel metal hydride battery designs are currently available that come close to meeting the battery performance requirements of PHEV designs that match the performance of conventional vehicles.

2. Nickel metal hydride cell and module designs incorporating the advances achieved in recent years for HEV batteries not only exceed these requirements but meet the requirements for PHEVs that can attain conventional vehicle performance in the battery-only (ZEV) driving mode. Prototypes of these battery designs are currently available in limited production quantities and are being tested in experimental PHEVs.

3. The cycle life capabilities of existing intermediate-power NiMH batteries appear sufficient for PHEVs of 40-60 miles electric range to attain about 130k-150k total vehicle miles (corresponding to 10 years of PHEV driving) over the life of these batteries.

4. The possibility of achieving even longer deep cycle life is suggested by recent BEV life test results and by the improvements achieved in nickel electrode charge acceptance at elevated temperatures. Testing of high power NiMH batteries beyond 2000 deep cycles is needed to determine if they can meet the cycle life requirements for PHEVs of shorter electric ranges with the original battery and without restricting the total number of miles in the battery-only mode during the vehicle life.

5. Lithium ion battery designs meeting all PHEV performance requirements exist now, but the deep cycling capability of these batteries is unproven. If the required cycle life and, equally important, adequate calendar life can be achieved in testing or through continued development, lithium ion batteries will become an excellent technical choice for PHEV applications.

6. Battery cost concerns are less serious for PHEVs than for full-size BEVs because PHEV batteries will have 50% to 75% smaller capacities. The hybrid comparison study [R-1] indicated that PHEVs with nickel metal hydride batteries of prospective mass production costs are likely to gain substantial market shares. Lithium ion batteries, although more expensive than nickel ion batteries in low-volume production, have potential for comparable or possibly lower costs in mass production.

The overall conclusions are that nickel metal hydride batteries designed for PHEV applications and incorporating the design and materials advances of the last 3-5 years should meet PHEV performance and cycle life requirements and, in mass production, also the cost goals for PHEVs to capture substantial shares of the automobile market. NiMH battery designs are available now with performance and cycle life sufficiently close to requirements to justify evaluation of PHEV prototype vehicles. NiMH batteries meeting all requirements – including full power for the battery-only driving mode – could very likely be fabricated on a pilot scale within a few years. Assuming sufficient demand develops for such batteries, one or more plants with sufficient capacity for about 10,000 PHEV battery packs could be established within an additional 2-3 years.

Lithium ion batteries have the needed performance, but the adequacy of their deep cycle and calendar lives for PHEV applications remains to be proven. If appropriate efforts were initiated, it should be possible to assess the feasibility of Li ion batteries for PHEV applications within 2-3 years. On that basis, Li ion technology for PHEV applications probably would be 3-5 years behind NiMH batteries.

The NiMH battery design and materials improvements achieved, and the BEV battery cycle life capabilities demonstrated in the last few years also have improved battery prospects for BEVs. The introduction of PHEVs on a broad scale should result in battery production volumes that reduce costs sufficiently for full-size BEVs to capture increasingly significant niche markets. This is examined in detail in Sections 4 through 6.

Plug-in HEV Overview

Plug-in hybrid electric vehicles (PHEVs) – hybrid electric vehicles with externally recharged batteries of sufficient energy storage capacity to give vehicles significant range on battery power alone – promise to achieve most of the pollutant and carbon dioxide emissions reduction and petroleum savings benefits of battery-only electric vehicles, but at substantially lower battery and vehicle cost, and without the range limitations of BEVs. Equally important, compared to the power assist hybrid vehicles (HEVs) now being introduced commercially, PHEVs are expected to offer superior environmental characteristics as well as much-reduced petroleum consumption and carbon dioxide emissions[17]. Automobile manufacturers are, however, not yet pursuing the development and introduction of PHEVs, apparently because they are concerned about the availability and cost of batteries suitable, and the charging infrastructure required, for PHEVs. Some concerns have been expressed also about the willingness of prospective owners to plug in their PHEVs for battery recharging.

The hybrid vehicle comparison study[17] indicates that two of these concerns are unfounded: The great majority of prospective owners have access to the standard 120 Volt electric outlets required for recharging most PHEVs. Also, most of these owners expressed preference for plugging in at home to minimize trips to gas stations. Thus, the main barrier to the development and demonstration of PHEVs and their prospective benefits appears to be uncertainty whether batteries meeting PHEV requirements are available now or, at least, could become available in the near term.

These uncertainties are addressed in an ongoing continuation of the hybrid comparison study quoted above. Performance, life and cost data for state-of-the-art nickel metal hydride (NiMH) and lithium ion (Li ion) battery technologies (many of them developed for BEV or HEV applications) are being acquired from recent tests and in discussions with leading manufacturers/developers of such batteries. The information is being compared with the requirements (see below) for competitive PHEV batteries.

This comparison is not yet complete. In particular, confirmation of extensive deep cycling capabilities must still be sought through testing of batteries in modes representative of anticipated PHEV uses, and more confident cost predictions are needed for mass-produced PHEV-design batteries. However, it is important that the current debate of zero and near-zero emission vehicle regulatory and RD&D strategies take account of the positive trends in NiMH battery cycle life observed, and the improvements in design and materials achieved over the last several years. Accordingly, we summarize here interim findings that indicate good prospects for batteries to meet PHEV technical requirements – a key test for the feasibility of plug-in hybrid electric vehicles.

Plug-in HEV Battery Requirements: Performance and Life Cycle

The battery specific energy and power levels in Table 2-1 permit the 20-mile and 60-mile electric range PHEVs modeled in the comparison study[17] to match the performance of comparable conventional vehicles. Batteries with the performance parameters given in brackets would allow even PHEVs with shorter ZEV range (i.e., smaller batteries) to perform like comparable CVs in the battery-only driving mode.

The cycle life requirements in Table 2-1 are derived from the assumptions of 130,000 total vehicle miles in 10 years and annual averages of approximately 5,000 and 10,000 battery-only miles driven by PHEV-20 and PHEV-60 vehicles with their 6 kWh and 18 kWh batteries, respectively.

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[17] "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options", EPRI Technical Report 1000349, July 2001

Table 2-1
Electric and Hybrid Vehicle Battery Requirements (Module Basis)

Requirement Parameter		HEV	PHEV-20	PHEV-60
Vehicle ZEV Range	(miles)	0	20	60
Battery Capacity	(kWh)	<3	6	18
Cell Size[18]	(Amp-hours)	5-10	15-30	45-90
Specific Energy	(Wh/kg)	>30	~50 (≥50)	~70[19] (≥110)
Specific Power	(W/kg)	~1000	~440 (700 [20])	~390 (390[21], 550[22])
Cycle Life, deep	(80% DOD)	n.a.	≥2500	≥1500
shallow	(+/- 100 Wh)	200k	200k	200k

Battery Performance and Cycle Life Prospects

A number of electrochemical battery systems have been proposed for hybrid vehicle applications. Of these, lead acid batteries have low specific energy (excessive weight) and inadequate cycle life. Low specific energy also makes nickel cadmium batteries unattractive.

Among the advanced batteries promising high specific energy, systems with metallic lithium negative electrodes (e.g., the lithium polymer and lithium-sulfur systems) have not yet shown adequate deep cycle life. Sodium-nickel chloride ("ZEBRA") batteries have demonstrated very good cycle life in BEV service but specific power appears to be too low for HEV and PHEV applications. To date, only nickel metal hydride and lithium ion batteries are showing sufficient promise to be considered in the comparisons below.

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[18] Cell size ranges correspond to an assumed battery voltage range of 400V to 200V.

[19] With a battery of 70 Wh/kg, PHEV-60 vehicle weighs about 100kg more than the corresponding conventional vehicle.

[20] Higher specific power required because of higher power requirement for battery-only mode.

[21] Specific power sufficient for battery-only mode power requirement of 70 Wh/kg battery.

[22] Higher specific power required for battery-only mode power requirement of 110 Wh/kg battery.

Nickel Metal Hydride (NiMH)

Table 2-2 lists performance and cycle life data provided by battery manufacturers for NiMH batteries designed for HEV, BEV and other applications. No currently available technology meets every requirement. However, the OBC 45 Ah and 28 Ah medium-power designs have suitable cell sizes and sufficient specific energy and power to give both PHEV types competitive performance. Indeed, the PHEV models developed and used for hybrid vehicle comparisons [R-1] were based on these designs. The medium-power PEVE (mini-EV) and VARTA designs have sufficient specific energy but fall short of meeting specific power requirement.

A few years ago, PEVE made design changes that increased the specific power of its high-power NiMH batteries for HEVs by about 50% to more than 1000Wh/kg. This was accomplished without a significant loss of specific energy. Motivated by emerging markets for high power batteries, other manufacturers also achieved large increases in specific power. For example, we identified two developmental medium/high power designs (see Table 2-2) that appear to have the performance characteristics needed for PHEV-20 and PHEV-60 vehicles to match CV performance in the battery-only operating mode. Prototype cells and modules of these designs may become available in 2003.

The PEVE and VARTA medium-power designs promise to meet deep cycling battery life requirements for PHEVs with about 40 miles or longer ZEV range. Excellent deep cycling capability of NiMH batteries was confirmed by test data obtained during the Hybrid Control Strategy Evaluation Project performed by SMUD for DARPA, USABC and CARB in 2001. The Saft 100Ah BEV-design modules used in this test were cycled over a 60% capacity range for nearly 3000 cycles that correspond to about 2200 cycles at 80% depth-of-discharge (DOD). Judged from the 12% capacity decrease and less than 3% increase in internal resistance (at 50% DOD) at the conclusion of the test, these batteries had substantial cycling capability left.

These results are consistent with the general observation that the cycling capability -- expressed as the total number of kWh delivered by a battery over its life per kWh of storage capacity – of nearly all battery types increases substantially as the depth-of-discharge decreases. Because the batteries of PHEVs (especially those with longer ZEV ranges) will not be fully discharged every day before overnight recharging, they can be expected to deliver more lifetime cycles than achieved in uniform 80% DOD testing.

Table 2-2
Nickel Metal Hydride Battery Characteristics (Module Basis)

Manufacturer (Developer)	Battery Design	Cell Size (Ah)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Cycle Life (80% DOD)	Status[a] (year)
Texaco Ovonic Battery Systems (TOBS)	high power	7.5	~40	650	n.a.	pp (00')
	med. power	28	48	~440	?	pp (00')
	med. power	45	71	~390	?	d (00')
Panasonic EV Energy (PEVE)	high power	6.5	~40	>1000	n.a.	mvp (98')
	med. power	28	58	300	>1500	lvp (99)
	Full-BEV design	95	63	200	>1200	mvp (98')
VARTA	high power	10	30	630	n.a.	pp (98')
	med. power	45	50	220	>2000	pp (98')
Unnamed Developer	med/high power	25	55	500-800	?	d/pp (03')
		50	60	500-800	?	d/pp (03')

[a] d - developmental, pp - production prototype, lvp - low volume production, mvp - medium volume production

In addition, NiMH battery charge acceptance and retention at elevated temperatures (e.g., 50-60°C) has been improved substantially in recent years through special additives to the nickel oxide positive electrode. This advance reduces oxygen gassing and the heat release associated with oxygen recombination within battery cells, making further increases in deep cycle life likely. While the capability of NiMH medium/high power battery designs to deliver the equivalent of 2500 deep cycles (required for shorter ZEV range PHEVs) is unproven at present, the results obtained by SMUD (see above) are encouraging. Clearly, testing of NiMH medium/high power batteries beyond 2000 cycles should be undertaken to confirm their suitability for PHEVs with shorter ZEV ranges.

Lithium Ion (Li ion)

Table 2-3 lists performance and cycle life data provided by current developers of Li ion batteries for HEV and BEV applications. The comparison with Table 2-1 shows that current medium power/mini-EV designs meet the cell size and performance requirements for PHEVs covering the entire ZEV range in the battery-only driving mode.

Table 2-3
Lithium Ion Battery Characteristics (Module Basis)

Manufacturer (Developer)	Battery Design	Cell Size (Ah)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Cycle Life (80% DOD)	Status[a] (year)
SAFT (U.S.)	high power	8	74	1500	n.a.	pp('99)
	med. power	30	100	950	1000 (?)	d ('99)
GS/JSB (Japan)	high power	3	25	2000	n.a.	pp('02)
	med. power	24	37	1500	?	pp('02)
	mini-BEV design	40	70	700	?	pp('02)
	Full-BEV design	95	100	700	?	pp('02)

[a] d- developmental, pp- production prototype, lvp- low volume production, mvp- medium volume production

The critical questions to be answered for lithium ion batteries are whether their performance levels can be sustained over the time periods (e.g., 10 years) and the number of deep cycles (see Table 2-1) required for PHEV applications. Because the necessary capacity retention and cycle life data do not appear to be available, testing candidate designs under conditions simulating representative PHEV duty cycles is needed to properly assess the prospects of lithium ion batteries for PHEV applications.

Plug-in HEV Battery Costs

Like electric vehicle battery cost, the prospective cost of PHEV batteries has remained a concern especially of automobile manufacturers. However, because of their lower capacities, PHEV batteries are expected to cost 50% to 75% less than full-size (e.g. 30-35 kWh) BEV batteries. With projected battery costs of approximately $2,700 to $5,800 for a ZEV range capability of 20 miles to 60 miles[17], PHEV-20 and even PHEV-60 plug-in hybrid electric vehicles can expect to find markets because of their substantially lower ICE engine and operating costs compared to the HEVs now being marketed successfully.

The key assumptions underlying the battery cost estimates are that (1) in mass production the specific cost of nickel metal hydride battery modules are likely to drop to the $250/kWh level projected in 2000 by the California Air Resources Board's Battery Technical Advisory Panel (BTAP 2000), (2) for the same battery materials and annual production volume, the specific costs of modules designed for PHEV-60 and PHEV-20 batteries will be higher at $270/kWh and $320/kWh, respectively, and (3) balance-of-plant costs of about $800 need to be added to module costs to arrive at total battery costs .

Although the current cost of lithium ion batteries is higher for comparable applications than those of NiMH batteries, the cost projected for mass-produced BEV batteries is comparable or lower. For one, 70% fewer cells of the same size are required to fabricate a battery of the same capacity and voltage. Also, little or no need for changes and the associated cost increases are anticipated when going to PHEV designs inasmuch as BEV designs already have the specific power capabilities needed by PHEV batteries. Finally, the cost of the specialized materials contributing to Li ion battery cost can be expected to decrease more with high production volume than NiMH materials. As a result, the prospect for mass-produced Li ion batteries to meet the cost requirements for PHEV applications also can be considered encouraging.

3

ANALYSIS OF BATTERY COST AND LIFE PROJECTIONS FOR ELECTRIC-DRIVE VEHICLES

Long-Term Testing of Nickel Metal Hydride Batteries

There is a relative scarcity of real world data on the performance of nickel metal hydride batteries, partly due to their comparatively brief amount of time in the market. This report will summarize two important tests, a long-term evaluation of five RAV4 EVs by Southern California Edison and a unique hybrid control strategy test of battery cycle life by the Sacramento Municipal Utility District [R-4]. While additional testing is needed to further validate the results of these tests, they represent a strong indication that NiMH batteries for full-function battery EVs, plug-in HEVs, and city EVs can exceed previously anticipated cycle life requirements.

Long-Term Durability Test of NiMH RAV4 Electric Vehicles

In early 2000 Southern California Edison (SCE), in partnership with Toyota Motor Sales, U.S.A., Inc., initiated a test of five RAV4 Electric Vehicles (RAV4 EV) to evaluate the durability and reliability of the EV traction battery over a driving distance of 160,000 kilometers (100,000 miles) and beyond. Five vehicles were selected for the test: three 1998 conductively charged RAV4 EVs and two 1999 inductively charged RAV4EVs. These vehicles had been in continuous use in the SCE fleet since placed in service.

In January 2003 the 268 EVs of the SCE fleet were used primarily by meter readers, service managers, field representatives, service planners and mail handlers, and for security patrols and carpools. In 13 years of operation, the EV fleet had logged 8.8 million miles (14.2 million kilometers), eliminating more than 1,000 tons of air pollutants, and preventing the emission of 4,700 tons of tailpipe carbon dioxide emissions. The vehicles in the test fleet were also used as long-distance commuters and subjected to deep battery discharges and twice-per-day charging, often at elevated temperatures[23].

On November 7, 2002, the first of the five RAV4EVs in the test fleet reached the 100,000-mile target. A breakdown of the mileage accumulation of each vehicle, through January 24, 2003, is shown in Table 3-1.

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[23] Michel Wehrey and Naum Pinsky , Southern California Edison, Private Communication, October 10, 2002.

Table 3-1
Accumulated Mileage of RAV4-EV Test Vehicles

Vehicle Number	Odometer Reading miles (kilometers)
1	101,040 (162,608)
2	97,677 (157,196)
3	94,140 (151,504)
4	77,339 (124,465)
5	73,509 (118,301)

Figure 3-1 shows the breakdown of the mileage accumulation history of Vehicle No. 1. SCE and Toyota began the test project in February 2000 to obtain data on operating costs, vehicle efficiency, maintenance requirements, battery life, charging issues and other factors that are specific to the long-term use of EVs. Employees with long commutes drive the vehicles daily to and from work, at SCE facilities, either the headquarters in Rosemead, or its ISO 9001-certified Electric Vehicle Technical Center (EVTC) in Pomona.

Fleet data is confirming that EVs with nickel metal hydride batteries are compatible with a variety of mission requirements, and are cost-effective to operate. Not only are the EVs meeting the employees' driving needs, they are also very reliable, with little routine maintenance required. More importantly, the five-vehicle test is demonstrating the long-term durability of the nickel metal hydride battery. No significant performance degradation has been observed to date and SCE’s data provides strong evidence that all five vehicles will exceed the 100,000-mile mark. In addition to SCE’s positive experience, test data collected by other laboratories in the country and experiences reported by other fleets strongly suggest that many of these vehicles will have a 130,000 to 150,000 mile nickel metal hydride battery life. This points to the availability of NiMH battery designs capable of lasting for the useful lifetime of an electric vehicle, 10-15 years and 150,000 miles[24]

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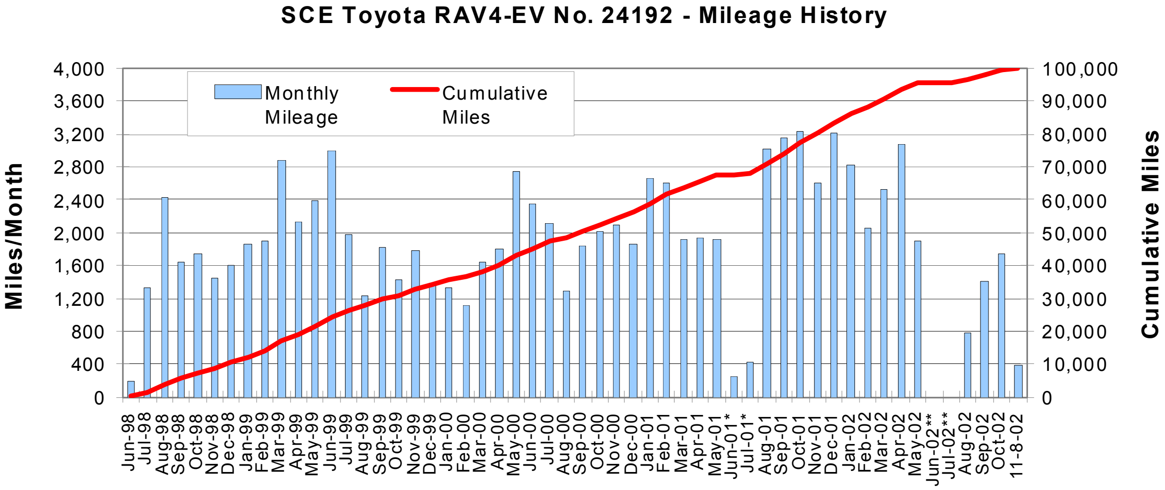
[24] This assumes that NiMH batteries can meet 10 year or 15 year calendar life expectations. The 2003 CARB Staff Report [R-8] recommends reducing battery warranty for HEV batteries to 10 years, 150,000 miles. While the prospects of NiMH batteries meeting these calendar life targets are considered relatively promising, additional development and testing is necessary to confirm that these goals are achievable.


SCE Toyota RAV4-EV No. 24192 - Mileage History

* Vehicle was left on charge for 62 hours and was in repair from 06/14/01 - 07/27/01.
**Vehicle was involved in an accident and was in repair from 05/28/02 - 09/14/02.

Figure 3-1
Mileage Accumulation for SCE RAV4-EV No. 1

Life Cycle Testing of NiMH Battery Packs on Different Hybrid Control Strategies

The original purpose of this test was to evaluate the effects of four distinct hybrid control strategies on nickel metal hydride batteries [R-4]. Four series strings of Saft NiMH, liquid-cooled, monoblock electric vehicle batteries underwent cycling. Two sets were cycled from 60% SOC to 40% SOC and two sets were cycled from 80% SOC to 20% SOC. The later pair of test batteries are the most interesting, as the 80% to 20% discharge is highly representative of a plug-in HEV discharge cycle.

The packs were cycled on a battery test bench using the SAE J1376 Central Business District (CBD) cycle. The CBD cycle and road load profile used to determine discharge characteristics were based on a heavy-duty transit bus. The battery was discharged on this cycle to 20% SOC then recharged to 80% SOC at a constant rate of 70 amps. One of the packs received a periodic grid recharge with 6-8% overcharge every 10 cycles. The results of this test are summarized in Table 3-2.

Table 3-2
Summary of NiMH Battery Cycle Life Tests

Pack	Hybrid Control Strategy	Total Cycles	Total Ah Discharged
Saft Pack A	80%-20% SOC, no grid charge	2,922	179,033
Saft Pack B	80%-20% SOC, grid charge every 10 cycles	2,841	178,033

The results of this test are impressive because they show tremendous capacity for deep discharge and recharge of the NiMH battery, even under heavy-duty charge-discharge conditions (similar to a heavy-duty bus). While this data is not identical to the HEVWG discharge profile (100%-20%, grid recharge, none or minimal overcharge) the cycle life seems to eclipse the HEVWG assumption of 1750 deep cycles [R-4], especially given that the test program concluded before the test packs had reached end-of-life conditions. The results from this test should serve to help build a roadmap for future testing of batteries to meeting PHEV performance and cycle life requirements.

It is understood that total lifetime energy throughput (often measured in total kilowatt-hours) for a battery increases nonlinearly as the cycle depth-of-discharge decreases. Shallower discharge cycles place less stress on the battery and improve cycle life. Figure 3-2 [R-11] shows this relationship for nickel metal hydride and two lead-acid battery designs. As DOD decreases, nonlinear increases in cycle life lead to significant increases in total energy throughput in the battery. This has the practical effect of extending battery life in a vehicle where SOC can be controlled (e.g. plug-in or power assist HEVs). For a PHEV, this results in both a greater capacity for all-electric travel before reaching end-of-life on the battery system and higher probability to design the system for 150,000-mile battery life.

These assumptions are also supported by Dr. Menahem Anderman, who confirms the benefits of shallower cycling regarding battery life, resulting in greater lifetime cycle capacity[25]. Dr. Anderman confirms some battery manufacturers using a 60% DOD discharge cycle[26] achieve 6,000 – 8,000 cycles[27].

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[25] Personal communication with Dr. Menahem Anderman, January 2003.regarding the battery manufacturers with a high degree of quality control.

[26] For example 90% to 30% or 80% to 20% SOC.

[27] Personal communication with Dr. Menahem Anderman, January 2003.regarding the battery manufacturers with a high degree of quality control.

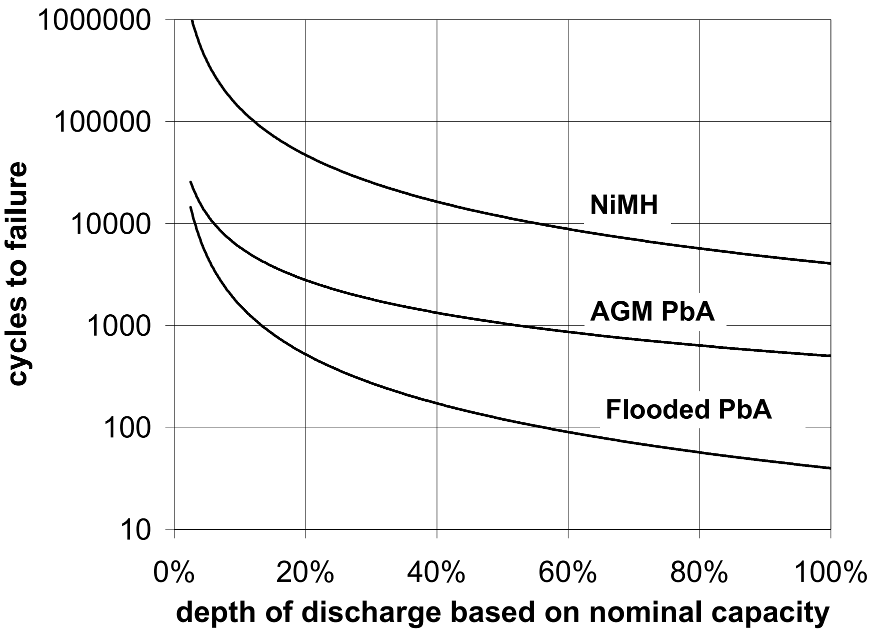

Figure 3-2
Battery cycles to failure versus depth-of-discharge [R-11]

Nickel Metal Hydride Cost and Availability

The following section draws heavily from the review and analysis of an important report from Advanced Automotive Batteries entitled, *The 2002 Industry Report – A Critical New Assessment of Automotive Battery Trends* [R-3]. This document, authored by Menahem Anderman[28], represents some of the best current knowledge of advanced automotive battery technology. The contents of the report focus on battery technologies for mild and power assist hybrid electric vehicles, providing key insight into the development of production battery products for the few hybrid programs in the marketplace. Dr. Anderman was also a member of the Year 2000 BTAP panel and the *2002 Industry Report* contains information that is an important extension to the final BTAP report, *Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability* [R-2].

Availability of production vehicle programs utilizing advanced batteries continues to be an obstacle to attaining battery cost reductions through increased volume. At the time of this report, there are as few as three production programs incorporating high power NiMH battery systems[29]. The last production full-function electric vehicle program supplying vehicles to fleets or public

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[28] The full report can be obtained by contacting Advanced Automotive Batteries at www.advancedautobat.com.

[29] A fourth production HEV, the Toyota Crown, uses a 42V VRLA battery.

customers[30], the Toyota RAV EV, was discontinued on January 12, 2003[31]. The low number of actual production contracts available for advanced batteries for either hybrid or electric vehicles limits the opportunity for battery manufacturers to make materials purchasing or capital investment decisions that can lower production costs.

Figure 3-3 places battery cost predictions from three different sources [R-1, R-2, R-3] in a plot of cost versus production volume. The first two sets of cost information are manufacturer's data provided in the BTAP 2000 report [R-2]. Both Panasonic EV Energy and Ovonic Battery Company[32] are in close agreement that long-term battery module prices for high specific energy NiMH designs can reach $250/kWh in high volumes. It is increasingly apparent that electric vehicles will not easily reach the high volumes of 100,000 or greater required and an estimate of $300/kWh to $500/kWh in more moderate numbers of 6,000 to 20,000 is more plausible.

The *2002 Industry Report* surveyed several manufacturers of high specific power NiMH batteries suitable for power assist HEVs [R-3]. High power modules are more complex in design and require more material per kWh of capacity. A near-term module cost of $700/kWh is projected in 2004 at anticipated volumes with a high volume prediction in 2010 of as low as $444/kWh, with $600/kWh more likely to occur.

The Hybrid Electric Vehicle Working Group established a cost relationship for power assist (HEV0) and plug-in (HEV20, HEV60) hybrid electric vehicle batteries based on available data [R-1]. These projections were developed for the 2010 timeframe assuming production volume of 100,000 vehicles. Figure 3-4 illustrates the projected relationship between battery module cost and power/energy (P/E) ratio.

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[30] There are currently no active programs in North America that make new full function or city EVs available. This situation could change in the near future. This scope of this report does not include low speed Neighborhood Electric Vehicles (NEVs), which are still sold to the general public.

[31] Source: http://www.evworld.com/databases/shownews.cfm?pageid=news120103-01

[32] Ovonic Battery Company manufactures NiMH batteries under a joint venture, Texaco Ovonic Battery Systems.

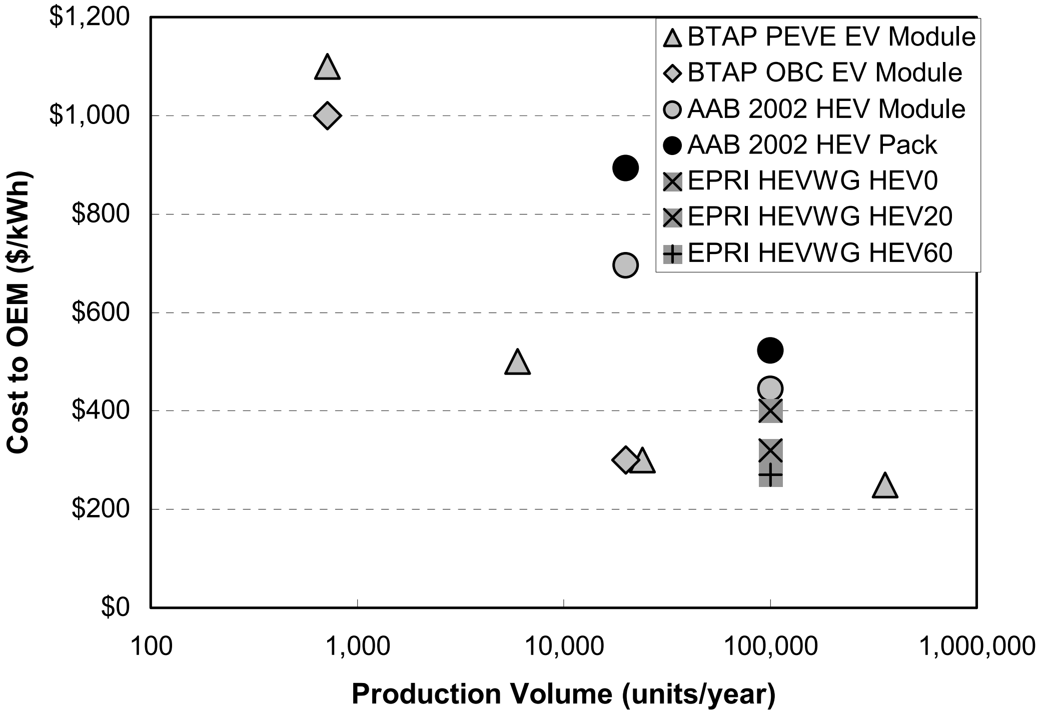

Figure 3-3
Combined Cost Estimates for NiMH Batteries for EVs and HEVs.

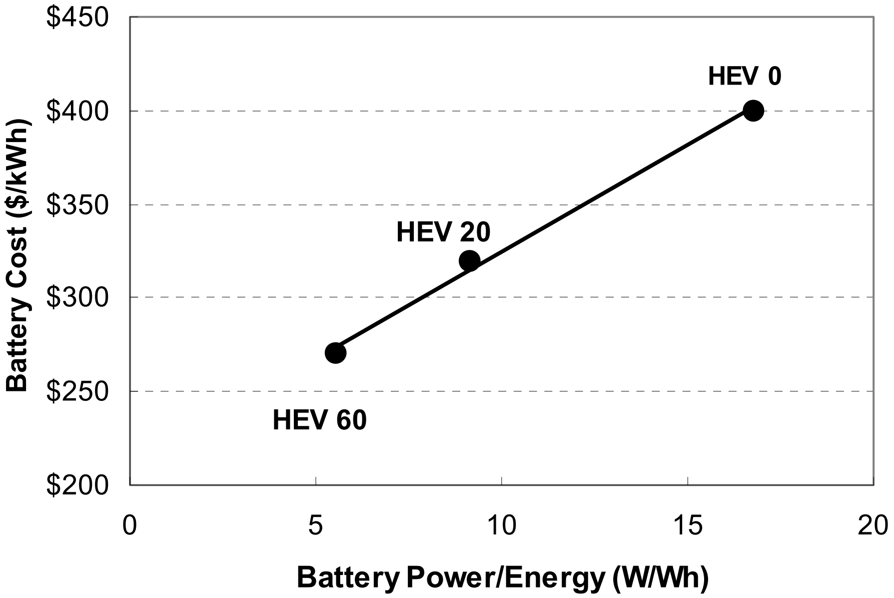

Figure 3-4
NiMH Battery Module Cost vs. Power/Energy Ratio [R-1].

It is important to note that the highest P/E ratio of the power assist hybrid battery is 16.7 and NiMH battery products are current demonstrating P/E ratios of 25 or higher.

Figure 3-3 illustrates the crucial relationship between production volume and cost and its implications for the electric-drive vehicle industry. There is currently one battery manufacturer, Panasonic EV Energy, producing NiMH HEV batteries for vehicles currently for sale in North America[33]. Introduction of additional hybrid models into the market will result in more battery production contracts and spur additional development[34]. As more automotive manufacturers introduce hybrid models into the marketplace, other battery vendors will have the opportunity to secure production contracts. There are currently 5-7 developers of automotive NiMH battery technology and an additional 5-7 developers of Li Ion technology [R-3]. A mature, reasonably consistent, and competitive market for advanced batteries is likely to encourage innovation, development, and cost reduction.

Lack of sustained EV production has impaired or halted battery product development for these vehicles. However with a current EV module cost of approximately $900/kWh in low production, these batteries appear to be following the projected cost-volume relationship in Figure 3-3. For HEV batteries, 2002 price quotes of $1,100/kWh in pack form also appear to be in line with the 2004 projection of $900/kWh. In conclusion, battery costs appear to be behaving very close to predictions made in the 2000-2002 timeframe. Higher production volumes of power assist hybrids[35] will help to create a mature market with multiple battery vendors and it will be easier to determine the mature cost of the technology.

Conclusions

- Expectations for nickel metal hydride batteries for BEVs have dramatically increased in the last three years. ARB staff in their August 7, 2000 staff report [R-5] expected NiMH BEVs in 2003 to last 6 years and 75,000 miles (about 1000 cycles from 100% to 20% SOC). Today, based on the four sources above, that it is reasonable to expect NiMH BEVs in 2003 without improved nickel electrodes can last 130,000 to 150,000 miles on the original pack (about 2000 cycles from 100% to 20% SOC). Proven calendar life is greater than 6 years, and it does not seem unreasonable to expect a calendar life of ten years or greater, especially with the new improved nickel electrodes.
- Similarly, based on the four sources above, it is reasonable to expect the potential for 130,000 to 150,000 miles on the original pack for plug-in HEVs, assuming that the system can effectively control state-of-charge and battery module temperature to maximize pack life.

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[33] Panasonic manufactures prismatic NiMH packs for the Toyota Prius and cylindrical NiMH packs for the Honda Insight and Civic hybrids.

[34] Sanyo is the current battery vendor for the Ford HEV Escape program and Saft for the 42V PSA hybrid (vehicle programs currently in development)

[35] The global market for hybrid is forecast at 567,000 vehicles in 2008.

- Improvements in the nickel electrode that have been developed are expected to improve the lifetime miles on the original pack. These improvements will make charging in hot weather much easier and make cooling systems for the battery much simpler and cost-effective.
- Shallower cycling of batteries (e.g. from 90% to 30% SOC) increases the cycle life substantially compared to typical deep cycles (e.g. 100% to 20% SOC). This results in substantially greater energy throughput over the lifetime of the battery pack, resulting in greater capacity for a PHEV to operate in the electric mode. While more laboratory and field testing is needed, these results suggest that BEVs and PHEVs with smaller battery packs (e.g. smaller city EVs or full function PHEVs with 10 kWh battery packs) can achieve significantly longer battery life than originally expected.
- The bottom of the cost / volume curve is different for different types of NiMH batteries: about \$235/kWh for BEVs, about \$270/kWh for PHEV 60s, about \$320/kWh for PHEV 20s and about \$400/kWh for HEV 0s.

4

LIFE CYCLE COSTS FOR HEVS AND PHEVS

Introduction

This section summarizes the life cycle cost methodology and results for mid-size sedan and full-size sport utility vehicle (SUV) platforms. Life cycle cost is defined as the overall cost to the vehicle operator, including vehicle purchase price, fuel costs, and maintenance costs over the life of the vehicle. The ARB developed an extensive life cycle cost model for the August 7, 2000 staff report [R-5]. This model included many different vehicle platforms and configurations, including power assist hybrids (HEV 0s), but did not include a PHEV 20 life cycle cost analysis. This section uses the ARB's basic model for an HEV 0 traveling 117,000 miles in 10 years, but updates it with cost data from the collaborative HEVWG studies [R-1, R-6], which were a result of a consensus reached among automakers, ARB, DOE, national labs, UC Davis, SCAQMD, EPRI, and utilities. For this report, the ARB model was expanded to include PHEV 20s and a lifetime scenario of 150,000 miles in 10 years[36]. The model was further refined using a method for estimating purchase price developed by Argonne National Lab (ANL) for the HEVWG studies. The data was used because it represented consensus reached between automakers and regulators and provided detailed component costs. The cost data used in the ARB analyses was not well documented and lacked the detailed component costs necessary to observe the results of small iterations in vehicle configuration. Furthermore, the manufacturer and dealer markup used by ARB only included a markup on the battery.

As described in the previous sections, it is assumed that NiMH battery life (with a wide range of power-to-energy ratios) can, in many cases, be extended to last 10 years/150,000 miles[37]. The vehicle configurations in this study were developed to remain within the battery life parameters developed in the first part of this study[38]. Therefore, it is the assumption of this life cycle cost study that original battery can meet a 10-year, 150,000-mile life[39]. This assumption is a combination of the very promising real-world driving experiences with Toyota RAV4 EVs, laboratory test data showing nearly 3000 deep cycles on NiMH batteries [R-4] and the

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[36] A 10-year, 150,000-mile target for vehicle life is a generally accepted benchmark.

[37] Calendar life is considered an issue for advanced batteries. NiMH is generally considered likely to meet a 10-year calendar life target, but more testing is needed to confirm this.

[38] The available data and real-world results for the cycle life capabilities of NiMH batteries from the top manufacturers are very promising. More testing, especially under real-world driving conditions, is necessary to confirm these assumptions for PHEVs.

[39] It is assumed that, in the 2010 timeframe, that the best hybrid system technology, utilizing high quality NiMH batteries will meet the lifetime requirements of the vehicle.

expectation that future advances in hybrid system technology and refinements in battery design will achieve this durability target. When battery replacement is not required during the vehicles expected life, the life cycle cost of HEVs and particularly plug-in HEVs (PHEVs) are substantially reduced. The analysis time frame was set towared the end of this decade in order to answer key questions: Given that millions of power assist HEVs are expected from Toyota, GM, Honda, Ford, Nissan and other OEMs by late this decade, and given that this mass production will bring down the cost of key shared electric drive components (e.g. motors, power inverters, etc.), how will this benefit plug-in HEVs? Is life cycle cost parity with power assist HEVs or conventional vehicles possible? If so, what annual production volume of plug-in HEV batteries is needed in order to reach life cycle cost parity? Data supporting the charts and tables in this section can be found in Appendix A.

Vehicle Designs and Platforms

Three vehicle designs of two vehicle platforms are compared and contrasted in this section. Only parallel hybrid configurations are considered in this study. In a parallel HEV, the combustion engine and the electric motor-battery combination can provide power to the drive axle(s) in parallel. HEVs may or may not have plug-in capability, that is, the ability to charge the batteries from a source of electric power such as the power grid. These plug-in hybrids can be operated in all-electric mode for a given distance (referred to as all-electric range or AER), utilizing only the battery and electric motor. Three vehicle designs were examined and compared:

- A conventional vehicle (CV) with an internal-combustion engine (ICE) that served as baseline for the comparisons of vehicle attributes
- A parallel hybrid with a high-power battery for power assist and regenerative braking but no plug-in capability and no all-electric range (HEV 0)
- A parallel hybrid that can operate like an HEV 0 but also has plug-in capability and a battery of sufficient capacity to provide about 20 miles of all-electric range (PHEV 20)

To study the above HEV designs, two platforms were considered. These include:

- A mid-size vehicle based upon a 2003 Ford Taurus LX with a 3.0L V-6 engine
- A full-size SUV based upon a 2003 Chevrolet Suburban 1500LS 4WD with a 5.3L V-8 engine

Life Cycle Cost Methodology

This study utilized an improved version of the California Air Resources Board (ARB) life cycle cost model used for the 2000 Zero Emission Vehicle Program Biennial Review (2000 ARB Staff Report [R-5]). The ARB staff model was selected because staff first commissioned a comprehensive review of many existing battery EV life cycle cost models, but did not use the most optimistic aspects of these other models. Since 2000, new information has become available on the lifetime mile capability of NiMH and the maintenance needs of electric drive vehicles. In addition, the HEV Working Group published its two comprehensive studies on HEV

0s and plug-in HEVs [R-1, R-6]. With this new information, several improvements were added to that model (more conservative and rigorous assumptions are marked with an asterisk *):

- Capability to model PHEVs was added (entails examining both the PHEV electric and gasoline miles driven.)
- Improved maintenance assumptions*
- High mileage lifetime assumptions (10 year/150,000 mile)
- Improved battery cost assumptions*
- Improved battery life (no battery replacement over life of vehicle)
- Improved battery second use assumptions*
- Incremental vehicle cost of HEVs based upon a cost based price method (Argonne National Lab/HEVWG method*)

This study's life cycle model compares vehicles based upon purchase price, fuel costs and maintenance costs similar to ARB's model. The model included assumptions on incremental purchase price, battery initial and replacement costs, battery life, maintenance costs and fuel costs. To calculate the life cycle cost of a vehicle, initial and annual costs are calculated for the lifetime of the vehicle. Annual costs are inflated over time using an inflation rate. To bring future costs to current 2003 dollars, a discount rate is used to calculate the net present value of future costs. This is the method used by ARB in the 2000 ARB Staff Report.

Basic assumptions used in the 2000 ARB Staff Report were also used in this study. These include an inflation rate of 3 percent, a discount rate of 8 percent, gasoline cost of $1.75 per gallon[40] and electricity cost of $0.05 per kWh. The low electricity cost is based upon off-peak charging. Changes in this study's methodology from the 2000 ARB Staff Report life cycle cost model (ARB Model) are discussed in the following subsections.

Improved Maintenance Assumptions

The original ARB Model used simplified maintenance assumptions that only provided average cost per mile for each technology. These assumptions are given in Table 4-1 for CVs, HEVs, and battery electric vehicles (BEVs).

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[40] Also used in Jan 10, 2003 ARB Staff Report: Initial Statement of Reasons: 2003 Proposed Amendments to the California Zero Emission Vehicle Program Regulations [R-8]

Table 4-1
ARB Maintenance Estimates (cents per mile)

Vehicle Type	Maintenance costs
CV	6.0¢ per mile
Freeway BEV	4.0¢ per mile
City BEV	3.5¢ per mile
HEV	7.5¢ per mile

Conventional vehicle maintenance costs were calculated using data from the Automobile Club of Southern California. The 2000 ARB Staff Report claims that the 6 cents per mile includes approximately 4.3 cents of estimated maintenance expenses, and 1.7 cents per mile of tire expenses. The reduced BEV costs were based upon review of the published life cycle cost studies and maintenance cost experiences from utility company fleets[41]. Maintenance costs for BEVs were assumed to be one-third less than CV maintenance costs, which includes increased tire costs for low rolling resistance tires used on BEVs. If the increased tire costs were assumed to be one third more per mile than the CV tire costs, (2.3 cents per mile) non-tire maintenance costs for BEVs would be 1.7 cents per mile versus 4.3 cents or roughly 60% less. HEV maintenance costs were assumed to be 25% more in the 2000 ARB Staff Report because the staff claimed additional costs for having both an electric and conventional drive system. In the third supplement to the Initial Statement of Reasons report (R-7, Third Supplement) ARB staff admitted that they were not aware of any significant scheduled maintenance costs that could be attributed to the vehicle battery and the electrical components of the powertrain and therefore revised the maintenance cost of HEVs to be equal to that of CVs.

In the 2001 EPRI report [R-1] on mid-size HEVs, a methodology was developed to address the differences in maintenance costs between CVs and various types of HEVs due to use of the engine. To estimate the difference in scheduled maintenance costs between CVs and HEVs, the HEVWG examined and quantified maintenance items that might be different between an HEV and a CV. Maintenance items related to the engine depend on the type of engine while the frequency at which this maintenance is performed is driven by the accumulation of operating miles on the engine. For a PHEV with both electric and hybrid driving modes, the engine does not accumulate operating time when the vehicle is in electric mode. For the purpose of this study, the engine maintenance is related to the number of miles driven as a charge-sustaining hybrid. The front brake replacements depend on vehicle miles, but with the assumption that since HEVs use regenerative braking, their brake pads are assumed to last more than twice as long. Rear brake service life was assumed to be the same for CVs and HEVs. Maintenance issues and costs should be reexamined in future studies, as more data on EV and HEV maintenance become available.

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[41] [R-5], page 108

Electrical components, such as traction motors and controllers, require very little maintenance. Brushless DC motors have no brushes to wear and the bearings are expected to last much longer than 10 years. Cooling of these motors must be robust, but many motors are now oil cooled. Power electronics are also very robust. IGBT chips are now being built with improved heat transfer to the heat sink, improved temperature tolerance, and ruggedized construction. These components are expected to last beyond 10 years with minimal maintenance.

Utility fleet experience over the last two years, based on millions of miles logged, has confirmed that scheduled maintenance on battery EVs can be extensively streamlined, and that maintenance costs should be lower than earlier estimates. For mature battery EV designs and vehicles produced by reputable manufacturers, SCE is recommending a cost of 1.2 cents per mile (including sales tax) for the first 90,000 miles and a cost of 1.9 cents per mile for the next 60,000 miles.[42] Several other sources are recommending even lower numbers. For example, ANL 1999 [R-15] estimates BEV maintenance is 0.53 cents per mile.

Using the above assumptions, various engine related maintenance items were determined for the two vehicle platforms. Maintenance costs (parts and labor) and frequency are given in Table 4-2 for the mid-size car and Table 4-3 for the full-size SUV.[43]

Table 4-2
Schedule Maintenance Costs for Mid-Size Car

Item	Frequency[a]	CV	HEV/PHEV
Engine Oil	3,000	$25.75	$22.40
Oil Filter	3,000	$14.00	$13.00
Fuel filter	15,000	$63.10	$63.10
Air Filter	30,000	$31.00	$26.00
Spark plugs	60,000	$68.10	$45.40
Timing Belt Replacement	100,000	$349.00	$349.00
PCV valve	100,000	$18.54	$18.54
Front Brake Pads	30,000/60,000[b]	$250.00	$250.00
Front Brake Rotors	60,000/120,000[c]	$236.00	$236.00

[a] Based on IC engine miles

[b] Front brake pads replaced every 30,000 vehicle miles for CVs, every 60,000 vehicle miles for HEVs

[c] Front brake rotors replaced every 60,000 vehicle miles for CVs, every 120,000 vehicle miles for HEVs.

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[42] Personal communication with Michel Wehrey of SCE, February 2003.

[43] Maintenance costs and frequency were taken from www.edmunds.com. Midsize car maintenance costs were for a 2003 Ford Taurus (3.0L) and SUV maintenance costs were for a 2003 Chevrolet Suburban (5.8L) 4WD in Los Angeles zip code 90012.

Table 4-3
Schedule Maintenance Costs for Full-Size SUV

Item	Frequency[a]	CV	HEV/PHEV
Engine Oil[b]	3,000	$29.00	$25.65
Oil Filter	3,000	$14.00	$14.00
Fuel filter	30,000	$39.56	$39.56
Air Filter[b]	30,000	$26.75	$24.25
Timing Belt Replacement	90,000	$230.00	$230.00
Spark plugs[b]	100,000	$147.80	$110.85
Front Brake Pads	30,000/60,000[c]	$280.00	$280.00
Front Brake Rotors	60,000/120,000[d]	$364.00	$364.00

[a] Based on IC engine miles

[b] Reduced oil, air filter, and spark plug costs only apply to PHEV 20. HEV 0 assumed same as CV.

[c] Front brake pads replaced every 30,000 vehicle miles for CVs, every 60,000 vehicle miles for HEVs

[d] Front brake rotors replaced every 60,000 vehicle miles for CVs, every 120,000 vehicle miles for HEVs

To account for other maintenance items common to CVs, HEVs, and PHEVs, a non-engine/brake related maintenance cost is added along with a tire maintenance cost. For both mid-size cars and SUVs, the non-engine/brake related maintenance costs are assumed to be 1.5 cents per vehicle mile and the tire maintenance costs 1.7 cents per mile. These added costs follow ARB's reasoning that there is no basis to assume non-engine related costs for HEVs would be higher or lower than for conventional vehicles [R-7]. In addition, the tire costs are the same for all technologies as the EPRI 2001 HEVWG study [R-1] used conventional tires for all base cases cited in this study. Based upon 150,000 lifetime miles, average maintenance costs per mile are given in Table 4-4.[44] For the actual, detailed analysis on maintenance see Appendix A.

In general, the maintenance analysis in this study is conservative for several reasons. First, maintenance costs are not escalated over time. The Complete Car Cost Guide 2000 shows how maintenance costs increases each year and also shows that for the second five years maintenance costs doubled to 10 cents per mile.[45] [R-16] Second, this analysis only includes scheduled maintenance and does not include repair costs. The Complete Car Cost Guide 2000 shows repair costs for a Ford Taurus at 1 cent per mile in the first 5 year, 70,000 mile period, and 3 cents per mile in the second 5 year period from 70,001 to 140,000 miles [R-16]. In neglecting to consider repair costs, an important expected benefit of electric drive vehicles is ignored. As discussed

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[44] Overall maintenance costs per mile turned out to be the same for the 2003 Ford Taurus and the 2003 Chevrolet Suburban. Average maintenance costs from the Complete Car Care Guide for 2000 showed average mid-size cars at 5.6 cents per mile and SUVs at 6.9 cents per mile for the first five years of operation. Since maintenance costs are used to compare across vehicle designs and not across vehicle platforms, this anomaly is not significant.

[45] Specifically, at 14,000 miles per year a Ford Taurus' maintenance per mile numbers jumped from 5 cents per mile to 10 cents per mile in the second five-year period.

earlier in this section, current experience in prior studies indicates that electric drivetrains will have lower breakdown frequency and require less preventative maintenance.

Table 4-4
Average maintenance costs per mile for a 150,000-mile life time

Platform	**Mid-size car**			**SUV**		
Vehicle Design	**CV**	**HEV 0**	**PHEV 20**	**CV**	**HEV 0**	**PHEV 20**
Engine/brake related	3.1¢	2.4¢	1.6¢	3.1¢	2.5¢	1.8¢
Non-Engine/brake related	1.5¢	1.5¢	1.5¢	1.5¢	1.5¢	1.5¢
Tire related	1.7¢	1.7¢	1.7¢	1.7¢	1.7¢	1.7¢
Total	6.3¢	5.6¢	4.8¢	6.3¢	5.7¢	5.0¢

Higher Mileage Assumption

The ARB's 2003 rulemaking [R-8] reduces the warranty requirement on HEV storage batteries for advanced technology partial zero emission vehicles (AT PZEVs) from 150,000miles/15 years to 150,000 miles/10 years, therefore life cycle costs should be addressed for CVs and HEVs traveling 150,000 miles in 10 years. A mileage accumulation schedule 25% higher than the original ARB life cycle model schedule was devised and is shown in Table 4-5. The original ARB mileage accumulation schedule of 117,000 miles/ 10 years was also analyzed in this study.

Table 4-5
Mileage Accumulation Rates for life cycle costs

Year	Annual Miles	Total Miles
1	16,690	16,690
2	16,273	32,963
3	15,866	48,829
4	15,469	64,298
5	15,083	79,381
6	14,705	94,086
7	14,338	108,424
8	13,979	122,403
9	13,630	136,033
10	13,289	149,322

Battery Cost Assumptions

In the 2000 ARB Staff Report, ARB provided some cost cutting assumptions on nickel metal hydride (NiMH) battery costs for both 2003 and in volume production. For this analysis, the authors used estimated costs determined in the EPRI HEVWG study [R-1]. These costs are compared in Table 4-6.

Table 4-6
Battery EV NiMH Battery Cost Assumptions

Assumption	ARB 2000 Report for BEVs		EPRI Assumptions
	2003	Volume	
Module cost[a]	$300 per kWh	$235 per kWh	Varied[b]
Added cost for pack	$40 per kWh	$20 per kWh	$680 + $13 per kWh[c]
Multiplier for manufacturer and dealer mark-up	1.15	1.15	Varies[c]
Battery life assumptions	6 years	10 years	10 years

[a] Equivalent module costs for an HEV 0 battery is $480 for 2003 and $384 for volume. Equivalent module costs for a PHEV 20 battery is $376 for 2003 and $301 for volume. HEV 0 and PHEV 20 batteries have a higher power to energy ratio and are more costly. These figures are calculated based on Figure 3-3.

[b] Battery module costs were varied in this analysis to determine the effect of battery module cost on life cycle cost.

[c] Manufacturer and dealer mark-up for HEV 0 battery modules estimated at $800, PHEV 20 battery modules $850, pack hardware mark-up assumed to be 1.5. Method documented in 2001 EPRI HEV report.

As stated in Sections 2 and 3, NiMH batteries from the top manufacturers have the potential to deliver at least 2000 cycles when regularly cycled to 80% depth-of-discharge (DOD)[46]. Additional test results, literature, and expert opinions indicated that reducing depth-of-discharge (DOD) to 60% or 70% will further increase pack cycle life. In this analysis, it is assumed that if a 70% DOD cycle is used, a NiMH battery from a manufacturer with rigorous quality control will last at least 3000 cycles for EV miles[47]. If a 60% DOD cycle is used, a NiMH battery is assumed to last 4000 cycles for EV miles. This effect is shown in Figure 3-2 [R-11], and has been conceptually supported by Dr. Menahem Anderman[48]. The impact of this practice is shown in Table 4-7, which shows that if battery size is kept constant while DOD is decreased, lifetime energy throughput increases. This has the effect of increasing the vehicle mileage and life on a given battery pack.

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[46] This is equivalent in going from 100% state of charge (SOC) to 20% SOC on every discharge cycle.

[47] In addition to an “EV-style” discharge to it minimum operating SOC, the battery is then subjected to a higher frequency, shallow charge/discharge profile (charge-sustaining operation) characteristic of a power assist hybrid. It is assumed that the higher capacity of the PHEV battery to deliver both power and energy will allow it to meet this requirement as well. Additional testing is needed to confirm this.

[48] Personal communication with Dr. Menahem Anderman, January 2003.

Table 4-7
Cycle life comparisons for a 10 kWh PHEV battery pack operating in EV mode

DOD	Lifetime Deep Cycles	kWh per cycle	Lifetime kWh
80%	2,000	8	16,000
70%	3,000	7	21,000
60%	4,000	6	24,000

Battery Second Use Assumptions

In the 2000 ARB Staff report, battery salvage value is estimated at $40 per kWh for NiMH BEVs at the end of 10 years and proportionally more if the battery had years remaining on it.[49] On the other hand, ARB assumed that HEV 0 batteries lasted 10 years, having a salvage value of $40 per kWh at the end of its life. The authors have used this assumption for HEV 0 batteries, but have been more conservative for PHEV batteries. This study assumes that PHEV 20 batteries could last longer that the 10-year/150,000 mile warranty period depending upon depth-of-discharge of each discharge cycle. In these cases, EPRI has estimated the battery salvage value as the projected new module cost at time of salvage multiplied times the percent of life remaining in the battery times the original kWh of the battery. This is based on the assumption that PHEV NiMH batteries will have second use past their original 10 vehicle years, and the value is proportional to the remaining energy. In the cases studied so far for PHEV 20s – the second use value is low – at about $15/kWh. (See Tables A-14, A-15, A-18, and A-19 in Appendix A.)

Miles from Off-Board Electricity versus Miles from Gasoline

PHEVs that charge batteries from the electric grid can provide a portion of their vehicle miles in all-electric mode. The amount of miles that a PHEV can drive in all-electric mode depends upon the battery size and the controller assumptions. In this analysis, the battery was assumed that 95% of its life was used during the lifetime assumption. Total electric miles for mid-size cars and SUV are shown in Table 4-8.

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[49] For example, ARB has cases were the battery is replaced in year 6. The second battery at the end of year 10 had 2 years of remaining useful life. Instead of assigning a $40/kwh second use value, it was given a value equal to one-third its original value, because one-third of its assumed useful life remained.

Table 4-8
All-electric operation of PHEV 20s

Vehicle Type	Mid-Size Car			SUV	
Mileage Assumption	Low	High	High	Low	High
Battery Size, kWh	5.88	5.88	8.00	9.30	11.00
Depth-of-discharge Assumption	80%	80%	60%	80%	70%
Cycle Life	2,000	2,000	4,000	2,000	3,000
Miles per Charge	20.1	20.1	20.5	21.0	21.7
Maximum Electric Miles	40,214	40,214	82,070	41,908	65,059
Miles operated all electric	38,204	38,204	77,976[50]	39,813	61,806
Percent of miles operated all-electric	32.7%	25.6%	52.2%	34.1%	41.4%

Retail Price Equivalent

Incremental vehicle costs in this study were calculated using a cost based price method developed by Argonne National Laboratory (ANL) for the Hybrid Electric Vehicle Working Group (HEVWG). This method is detailed in the 2001 EPRI HEV report.[51]

The ANL method assumes that electric drive components (drive motor, controller, and battery) are supplied by outside vendors. Their costs include not only the cost of labor and materials, but also a partial mark-up that includes some research and development costs, supplier overhead and profit, and appropriate warranties. Different mark-ups are applied to component costs depending on whether the vehicle manufacturer or a supplier builds them. A single mark-up covers manufacturer and dealer mark-ups and development costs. The ANL retail price equivalent (RPE) method does not include cross-product-line subsidies that are used in customer-based or competition-based pricing methods. These pricing methods, detailed in an EPRI report [R-12] and updated in a Green Car Institute report [R-13], show how automakers price vehicles using other considerations. As stated in these reports, auto manufacturers price vehicles differently to keep up with the competition, to capture new markets (e.g., fleets, young people), to establish or keep a reputation (e.g. technologically advanced or environmentally sensitive), or to sell cars that help it meet fleet average fuel economy standards (CAFE). A cost based pricing method is often used for mid-size cars, but for compact cars, and SUVs, it is much more difficult to develop an RPE because of all the above factors. SUVs, in particular, have much more pricing flexibility.

Costs of brushless permanent magnet (BPM) motors used in EVs and HEVs vary from vendor to vendor, depending mostly on production volume. Currently such motors are produced in the

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[50] Based on commuter charging at home and work each day.

[51] ARB's method could not be used as it includes no details on component costs and appears to include dealer and manufacturer profits, and indirect costs only for the battery. An alternative method used by United States Environmental Protection Agency was discussed by the HEVWG, but the ANL method was used because it was more sophisticated and applicable for HEVs.

20,000 units per year range, but it is assumed by 2010 that these motors will be produced in the 100,000 units per year range due to increased sales of HEVs. Additional cost reductions can be realized if permanent magnets are also used in other applications. While the HEVWG used approximately $16 per kW [R-1], costs as low as $10.50 per kW could be realized if permanent magnets are also used in other large volume applications. [R-9]

Motor controllers are also currently produced in low volumes. However, if IGBTs used in these controllers are also used in fuel cells and distributed power systems, the HEVWG estimated that a motor controller for an HEV would cost in the range of $10 per kW. [R-1]

Because this study's timeframe is volume production or end of this decade for most OEMs, the cost of motors, controllers and electric drive components (except PHEV 20 batteries) are near the bottom of the cost curve – specifically at 100,000 units per year of more. This is a key basis of the entire study. This is based on recent announcements by automakers to aggressively pursue engine-dominant HEV 0s. Toyota has announced plans to increase the number of HEV models to more than 10 by 2006 from its current three.[52] Toyota's goal of 300,000 HEVs by middle of this decade has been widely quoted, but less well-known is Toyota's President, Fuji Cho, in his efforts to make Toyota the world's number one automaker, wants HEV sales to reach one million per year by 2010.[53] In a New York Times feature story on HEVs, 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. [54] GM, in fact, has announced plans for 5 new HEVs by 2007 with 1 million GM HEVs expected by end of the decade.[55] GM CEO G. Richard Wagoner Jr. made "resoundingly clear that GM would not be left behind in the race with Japanese automakers for more fuel-efficient cars."[56] Nissan's goal is 100,000 per year by 2011.[57] Honda already sells two HEVs in the US with several others in the works including a hybrid EV performance car. Fords plans to launch an HEV version of its Escape SUV by 2004. Several other OEMs have announced HEV plans.

Total vehicle prices (cost based price using the ANL method) less energy storage system prices (cost based price using the ANL method) are shown in Table 4-9 for the mid-size car and Table 4-10 for the full-size SUV for the CV, HEV 0, and PHEV 20 designs. The mid-size car costs were calculated from the 2001 EPRI HEV report [R-1], the full-size SUV costs from the 2002 EPRI HEV report [R-6].

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[52] Kyodo news, Nov 6, 2002

[53] Lexington Herald, Jan 29, 2003 "Oh, What a Leader, Toyota head wants company to be world's number one carmaker."

[54] New York Times, Jan 28, 2003.

[55] News York Times, Dec 25, 2002 "GM to Offer 5 HEV Models by 2007"

[56] Business Week, Feb 26, 2003.

[57] Financial Times, September 29, 2002, "Toyota Says Hybrid Car Making Money"

Table 4-9
Mid-size car prices less battery using the ANL cost-based price method

Specifications	CV	HEV 0	PHEV 20
Engine Power, kW	127	67	61
Engine Type	V-6	I-4	I-4
Traction motor, kW	--	44.3	51.3
Glider	$11,525	$11,525	$11,525
Engine + Exhaust	$4,715	$2,888	$2,741
Transmission	$2,090	$1,250	$1,250
Accessory Power	$420	$535	$535
Electric Traction	$80	$2,084	$2,313
On Vehicle Charging System	—	—	$690
Total Price less Battery	$18,860	$18,282	$19,054
Incremental Price less Battery	--	($547)	$224

Table 4-10
SUV prices less battery using the ANL cost-based price method

Specifications	CV	HEV 0	PHEV 20
Engine Power, kW	212	145	115
Engine Type	V-8	V-8	V-6
Traction motor, kW	--	65.3	98
Glider	$27,022	$27,022	$27,022
Engine + Exhaust	$7,490	$5,984	$4,447
Transmission	$2,400	$1,600	$1,600
Accessory Power	$488	$608	$608
Electric Traction	$100	$2,770	$3,838
On Vehicle Charging System	—	—	$690
Total Price less Battery	$37,500	$37,985	$38,206
Incremental Price less Battery	--	$485	$706

Cost Benefit to OEM – Meeting CAFE Requirements

By producing HEV 0s, PHEV 20s, and City EVs, automakers are better able to comply with the federal fleet average requirements for car and truck fuel economy referred to as Corporate Average Fuel Economy (CAFE)[58]. Vehicles with electric miles from off-board sources of

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[58] [R-1], Section 6.

electricity receive considerable additional credit in CAFE as a result of the 1988 Alternative Motor Fuels Act.

As discussed in the retail price equivalent subsection, automakers typically consider the benefits of CAFE compliance when pricing small and large vehicles (e.g. subcompact cars, compact cars, full-size SUVs) and this results in internal cross-product line subsidies. Studies suggest this value is large [R-9, R-10, R-13] because it facilitates increased vehicles sales of larger, often highly profitable vehicles. The value to each Original Equipment Manufacturer (OEM) depends on its unique mix of models in the separate CAFE requirements for cars and trucks. Last year, an omnibus energy bill nearly made it to the President that would have changed CAFE to allow trading between an OEMs car and truck compliance requirements[59]. Should this become law in the near future, this would probably increase the use and value of cross-product line subsidies by OEMs.

However, according to Rubin and Lieby in Energy Policy magazine [R-14], the value of avoiding CAFE fines is $1100 - $2000 per vehicle. While the benefit to most OEMs of a cross-product line subsidy is probably larger, its value is very difficult to estimate. For the purposes of this study, we suggest the fine avoidance benefit is a reasonable, conservative surrogate for the value of the cross product line subsidies, and suggest a value of $500 for an HEV 0, $1000 for a PHEV 20 and $2,000 for a City EV. The increasing value is due to the larger fuel economy benefit for the different these three vehicles. Based upon the Alternative Motor Fuels Act (AMFA) of 1998, fuel economy used for CAFE purposes for dual fuel vehicles that operate at least 7.5 miles urban or 10.2 miles highway, is calculated as operating 50 percent of the time on electricity with a petroleum equivalency factor of 82.049 kWh/gasoline gallon. Single fuel vehicles, such as the City EV use the 82.049 kWh/gasoline gallon factor for 100% of their fuel economy. Both PHEV 20s and BEV 40s qualify for this AMFA credit. CAFE fuel economies using AMFA credits are shown in Table 4-11 for mid-size cars and SUVs. AMFA credits for City cars are shown in Table 4-12.

Table 4-11
CAFE fuel economy for mid-size sedans and SUVs with AMFA credits (mpeg)

Vehicle Design	Midsize Cars	SUVs
CV	28.9 mpg	18.2 mpg
HEV 0	41.9 mpg (45% increase)	27.6 mpg (50% increase)
PHEV 20	75.6 mpg (161% increase)	51.1 mpg (181% increase)

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[59] HR 4

Table 4-12
CAFE fuel economy for City Cars with AMFA credits (mpeg)

Vehicle Design	City Cars
CV	45 mpg
BEV 40	410.2 mpg (900% increase)

Note while the City EV mpg in CAFE is over 9 times higher than the equivalent CV and the PHEV 20 is about 1.6 to 1.8 times higher, its benefit to the carmaker is not equally large. This is because with increasing fuel economy there is a decreasing value to the carmaker, due to the use of a harmonic average formula in CAFE [R-1]. With this formula there is relatively more benefit for a small increase in fuel economy. On a value per mpg increase if the HEV, PHEV or BEV replaced 5% of the fleet, the $500 for the HEV 0, $1,000 for the PHEV 20 and $2,000 for the BEV 40 provide equal costs of benefits per mpg increase. Since the $500 for the HEV 0 is a half to a quarter of the value of fine avoidance predicted by Rubin and Lieby, the values of CAFE benefits assumed in this study are conservative.

Results

The following section describes the changes in results using the EPRI life cycle model compared to the ARB life cycle model used in the 2000 ARB Staff Report and in some cases updated ARB assumptions used in the 2003 ARB staff report.

Fuel Economy Costs

In the 2000 ARB Staff Report, fuel economies were estimated based upon projections of best in class vehicles. In this study, data from the 2001 and 2002 EPRI reports were used. These fuel economies were generated using the ADVISOR (ADvanced VehIcle SimulatOR) computer program developed by the National Renewable Energy Laboratory (NREL) with support from Department of Energy (DOE) [R-1]. Fuel economy comparisons are shown in Table 4-13.

Table 4-13
Fuel Economy Comparisons between EPRI model and 2000 ARB Staff Report (miles per equivalent gasoline gallon)[a]

	Mid-Size Car[b]			Full-Size SUV[c]		
Estimate	**CV**	**HEV 0**	**PHEV 20**	**CV**	**HEV 0**	**HEV 20**
ARB	35	55	--	25	40	--
EPRI	29	42	55[d]	18	28	37[e]

[a] Fuel economies represent a harmonic average of city and highway uncorrected fuel economies using 55% city and 45% highway. No real world correction factors are applied similar to ARB's analysis.

[b] ARB equivalent Mid-size cars: CV – Vehicle 28, HEV 0 – Vehicle 24

[c] ARB equivalent Full-size SUVs: CV – Vehicle 28.1, HEV 0 – Vehicle 24.1

[d] Represents a gasoline-only fuel economy of 43.5 mpg and an all-electric fuel economy of 0.285 kWh/mi.

[e] Represents a gasoline-only fuel economy of 29.5 mpg and an all-electric fuel economy of 0.433 kWh/mi.

Using the more conservative EPRI fuel economy estimates, the net present value of fuel economy is shown in Table 4-14. These represent vehicles produced in the later part of this decade. These results are considered somewhat conservative, as they assume that the CV, HEV 0 and PHEV 20 vehicles do not utilize any technological advances to the vehicle chassis to improve fuel economy, including lightweight materials, low-rolling resistance tires, or reduced aerodynamic drag.

Table 4-14
Net present value of life cycle fuel costs over 10 years

Lifetime Miles	Mid-Size Car[a]			Full-Size SUV[b]		
	CV	HEV 0	PHEV 20	CV	HEV 0	HEV 20
116,730	$5,401	$3,725	$2,787	$8,576	$5,655	$4,145
149,322	$6,894	$4,755	$3,037	$10,947	$7,219	$4,979

Maintenance Costs

The net present value of maintenance costs is shown in Table 4-15 and compared against that calculated in the 2000 ARB Staff Report modified by the Third Supplement.

Table 4-15
Net present value of life cycle maintenance costs over 10 years

Source	Lifetime Miles	Mid-Size Car[a]			Full-Size SUV[b]		
		CV	HEV 0	PHEV 20	CV	HEV 0	HEV 20
ARB[a]	116,730	$5,351	$5,351	--	$5,351	$5,351	--
EPRI[b]	116,730	$5,445	$4,733	$4,044	$5,408	$4,707	$4,024
	149,322	$7,133	$6,329	$5,042	$7,113	$6,369	$5,374

[a] From 2000 ARB Staff Report modified per Third Supplement
[b] This study

The main difference between the ARB estimates and the EPRI estimates is that ARB calculated maintenance costs based upon a fixed cost per mile, while the EPRI study examines maintenance cost items for the engine and brakes that are different between the different platforms. The Third Supplement Amendment to the 2000 ARB Staff Report [R-7] states that "*…staff is unaware of any significant additional scheduled maintenance costs that could be attributed to the vehicle battery and the electrical components of the powertrain. Therefore, maintenance costs should be limited to the vehicle's ICE and other conventional vehicle components*." The results presented in this study take ARB's comments to heart and examine the differences between the various platforms ICE and other conventional vehicle components in a more detailed way.

Battery Module Costs

In the 2000 ARB Staff Report, staff use a fully marked up battery cost of $391 per kWh for 2003 and $291 per kWh for volume production in the future for BEVs. The BEV battery module cost (without mark-up and associated battery systems used by ARB staff is $300 and $235 per kWh respectively. ARB used the same battery module costs for HEV 0s in the 2000 Staff Report, however due to the higher power to energy ratios needed for HEV 0s, these translate into $480 for 2003 and $384 for volume. Equivalent module costs for a PHEV 20 battery is $376 for 2003 and $301 for volume.[60] These higher costs are calculated based on Figure 3-3 and Figure 4-1. In the 2000 Battery Advisory Panel Report [R-2], module cost estimates versus production volumes were given and that figure is reproduced in Figure 4-1.

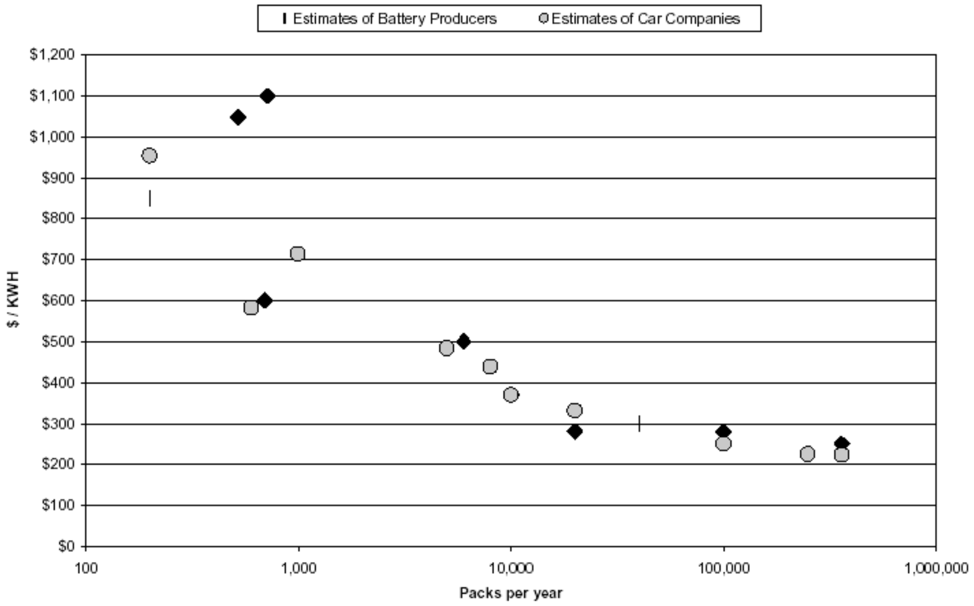

Figure 4-1
Cost Estimates for NiMH Battery EV Modules (from 2000 BTAP Report [R-2])

In the 2001 EPRI HEV report, battery module costs to the OEM of $400/kWh for an HEV 0 and $320/kWh for a PHEV 20 based upon producing 100,000 mid-size cars per year. In the 2002 EPRI HEV report on SUVs, battery module costs of $402/kWh for an HEV 0 and $352/kWh for a PHEV 20 based upon producing 100,000 full size SUVs per year (supplied by one battery manufacturer). These numbers are used in this study as well, and are calculated based on Figure 4-1 and Figures 3-2 and 3-3 in Section 3.

Conclusions

Without considering incentives of carmakers to modifying the retail price to capture image, market share or new buyers or to pass along their CAFE benefits, HEV 0s can reach life cycle cost parity with their conventional counterparts in some situations expected mid to late this decade. In the lower mileage 117,000-mile/10-year scenario, life cycle parity is reached when the battery module price for the mid-size car is $385 per kWh and $255 per kWh for the SUV. These are below the EPRI HEVWG minimum battery prices of $400 per kWh for the mid-size car and $402 per kWh for the SUV. Life cycle costs using the 117,000-mile/10-year life assumption for

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[60] ARB did not use these higher costs in the August 7, 2000 staff report, and appears not to have used them in the Jan 10, 2003 staff report. This study and the series of EPRI HEV Working Group studies [R-1, R-6] do account for this.

the mid-size HEV 0 using the two different battery price assumptions are shown in Table 4-16 and compared against the CV. Life cycle costs for the SUV HEV 0 using the two battery cost assumptions are shown in Table 4-17 and compared against the CV. As shown in Table 4-16 below, the mid-size car only misses cost parity with the CV by $41 in the net present value of life cycle costs when the EPRI HEV minimum battery price is used.

Table 4-16
Net present value of life cycle costs over 117,000 miles/10 years for mid-size HEV 0

Vehicle Type	CV	HEV 0	
Battery Module Cost, $/kWh	--	$385[a]	$400[b]
Incremental Vehicle Cost	--	($547)	($547)
Energy Storage System Cost	$60	$3,047	$3,091
Fuel Costs	$5,401	$3,725	$3,725
Maintenance Costs	$5,445	$4,733	$4,733
Battery Salvage Costs	--	($54)	($54)
Total Lifecycle Costs	$10,906	$10,903	$10,947

[a] Battery module price at which life cycle parity with CV occurs

[b] EPRI HEVWG minimum battery price

Table 4-17
Net present value of life cycle costs over 117,000 miles/10 years for SUV HEV 0

Vehicle Type	CV	HEV 0	
Battery Module Cost, $/kWh	--	$255	$402
Incremental Vehicle Cost	--	$485	$485
Energy Storage System Cost	$60	$3,295	$4,058
Fuel Costs	$8,576	$5,655	$5,655
Maintenance Costs	$5,408	$4,707	$4,707
Battery Salvage Costs	--	($96)	($96)
Total Lifecycle Costs	$14,044	$14,045	$14,808

[a] Battery module price at which life cycle parity with CV occurs

[b] EPRI HEVWG minimum battery price

When the vehicle lifetime assumption is increased to 10-year/150,000 miles, the battery module price for the mid-size HEV 0 to reach cost parity with the CV is $572 per kWh and $419 per kWh for the SUV using this study's assumptions[61]. The $572 per kWh for the mid-size HEV 0 battery pack is equivalent to $358 per kWh for a BEV battery pack and can be met

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[61] Cost-based pricing (ignoring tax breaks, CAFE benefits internal to the carmaker, or other factors), inflation, discount rate, electricity and gasoline price, maintenance, fuel economy and battery life, second use value, split of off-board electric vs gasoline-powered miles, cost of key components (e.g. motors, controllers, etc)

manufacturing about 15,000 BEV packs per year or 155,000 HEV 0 packs per year[62] based upon Figure 4-2. The key in this case is that "milder" HEVs that achieve 15 to 30% increase fuel economy[63] in medium production will bring down the cost of electronics and motors, or use of pricing strategies discussed earlier. It is unclear how much carmakers will rely on mild HEV 0s versus fully integrated HEV 0s that take full advantage of power assist, regenerative braking, idle stop, and other HEV 0 attributes. Life cycle costs using the 10-year/150,000-mile life assumption for the mid-size HEV 0 at the two different battery price assumptions are shown in Table 4-18 and compared against the CV. Life cycle costs for the SUV HEV 0 using the two battery cost assumptions are shown in Table 4-19 and compared against the CV.

Table 4-18
Net present value of life cycle costs over 10 years, 150,000 miles for mid-size HEV 0

Vehicle Type	**CV**	**HEV 0**	
Battery Module Cost, $/kWh	--	$572[a]	$400[b]
Incremental Vehicle Cost	--	($547)	($547)
Energy Storage System Cost	$60	$3,047	$3,091
Fuel Costs	$6,894	$4,755	$4,755
Maintenance Costs	$7,133	$6,329	$6,329
Battery Salvage Costs	--	($54)	($54)
Total Lifecycle Costs	$14,088	$14,088	$13,587

[a] Battery module price at which life cycle parity with CV occurs

[b] EPRI HEVWG minimum battery price

Table 4-19
Net present value of life cycle costs over 10 years, 150,000 miles for SUV HEV 0

Vehicle Type	**CV**	**HEV 0**	
Battery Module Cost, $/kWh	--	$419[a]	$402[b]
Incremental Vehicle Cost	--	$485	$485
Energy Storage System Cost	$60	$4,146	$4,058
Fuel Costs	$10,947	$7,219	$7,219
Maintenance Costs	$7,113	$6,369	$6,369
Battery Salvage Costs	--	($96)	($96)
Total Lifecycle Costs	$18,120	$18,122	$18,034

[a] Battery module price at which life cycle parity with CV occurs

[b] EPRI HEVWG minimum battery price

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[62] One generally accepted method for relating volume production costs for hybrid batteries is to use the cost curves for EV batteries (Figure 4-1) factored by a ratio of the energy in a full function EV pack (typically around 30 kWh) over the energy in the hybrid pack (2.91 kWh for the HEV 0 and 5.88 kWh for the PHEV 20 midsize sedans). This is a simplified assumption that is probably somewhat conservative, as it does not take into account the number quantity of cells produced as contributing to lower production costs.

[63] These HEVs use different batteries (e.g. "D" cell type batteries with even higher power to energy ratios), but can use the high voltage electronics and fairly large electric motors that can be used in the fully integrated HEV 0s in this study.

The prices used in the two mileage scenarios for HEV 0s do not include the estimated $500 benefit the HEV 0 brings to the carmaker in CAFE compliance benefits (See earlier subsection.) As carmakers often pass on these benefits to consumers, this will dramatically reduce life cycle costs, so that even low mileage cases can reach life cycle cost parity.

Without considering incentives of carmakers to modifying the retail price to capture image, market share or new buyers or to pass along their CAFE benefits, PHEV 20s can also reach life cycle cost parity with their conventional counterparts and HEV 0s under most conditions expected late this decade. Under the low mile assumption (10 years 117,000 miles), life cycle parity with the CV is reached when the battery module prices are $316 per kWh for the mid-size car and $337 per kWh for the SUV. These are below the EPRI HEVWG minimum battery prices of $320 per kWh for the mid-size car and $352 per kWh for the SUV, but the net present value of life cycle costs for those vehicles are just a few dollars more than that for the CV. Life cycle costs using the 10-year/117,000-mile life assumption for the mid-size PHEV 20 using the two different battery price assumptions are shown in Table 4-20 and compared against the CV. Life cycle costs for the SUV PHEV 20 using the two battery cost assumptions are shown in Table 4-21 and compared against the CV.

Table 4-20
Net present value of life cycle costs over 10 years, 117,000 miles for mid-size PHEV 20

Vehicle Type	**CV**	**PHEV 20**	
Battery Module Cost, $/kWh	--	$316[a]	$320[b]
Incremental Vehicle Cost	--	$224	$224
Energy Storage System Cost	$60	$3,893	$3,916
Fuel Costs	$5,401	$2,787	$2,787
Maintenance Costs	$5,445	$4,044	$4,044
Battery Salvage Costs	--	($43)	($44)
Total Lifecycle Costs	$10,906	$10,904	$10,927

[a] Battery module price at which life cycle parity with CV and HEV 0 occurs

[b] EPRI HEVWG minimum battery price

When the vehicle lifetime assumption is increased to 10 years, 150,000 miles, the battery module price for the mid-size PHEV 20 to reach cost parity with the CV is $380 per kWh and $427 per kWh for the SUV. The $380 per kWh for the mid-size PHEV 20 battery pack is equivalent to $297 per kWh for a BEV battery pack and can be met manufacturing around 150,000 PHEV 20 battery packs per year (30,000 BEV battery packs) based upon Figure 4-2. If a larger battery is used in a PHEV 20 with reduced cycle depth-of-discharge and extended cycle life, the mid-size PHEV 20 can reach cost parity with the CV at $471 per kWh and the SUV PHEV 20 at $455. The $471 per kWh for the mid-size PHEV 20 battery pack is equivalent to $368 per kWh for a BEV battery pack and can be met manufacturing around 45,000 of these slightly larger PHEV 20 packs (12,000 BEV battery packs). The conclusion that cost parity can be met with such low production volumes can promote growth of low-emission, high efficiency vehicles. This growth will further push battery prices down, increasing the attractiveness of PHEVs from both cost and environmental perspectives.

Table 4-21
Net present value of life cycle costs over 10 years, 117,000 miles for SUV PHEV 20

Vehicle Type	CV	PHEV 20	
Battery Module Cost, $/kWh	--	$337[a]	$352[b]
Incremental Vehicle Cost	--	$706	$706
Energy Storage System Cost	$60	$5,235	$5,375
Fuel Costs	$8,576	$4,145	$4,145
Maintenance Costs	$5,408	$4,024	$4,024
Battery Salvage Costs	--	($69)	($69)
Total Lifecycle Costs	$14,044	$14,041	$14,180

[a] Battery module price at which life cycle parity with CV and HEV 0 occurs

[b] EPRI HEVWG minimum battery price

Life cycle costs using the 10-year/150,000-mile life assumption for the mid-size PHEV 20 and the three different battery price assumptions are shown in Table 4-22 and compared against the CV. Life cycle costs for the SUV PHEV 20 using the two battery cost assumptions are shown in Table 4-23 and compared against the CV.

Table 4-22
Net present value of life cycle costs over 10 years, 150,000 miles for mid-size PHEV 20

Vehicle Type	CV	PHEV 20		
Battery Module Cost, $/kWh	--	$380[a]	$471[a]	$320[b]
Battery Size, kWh	--	5.88	8.00	5.88
Depth-of-discharge, % SOC	--	80%	60%	80%
Cycles to Failure Assumption	--	2,000	4,000	2,000
Incremental Vehicle Cost	--	$224	$224	$224
Energy Storage System Cost	$60	$4,269	$5,844	$3,916
Fuel Costs	$6,894	$3,822	$3,037	$3,822
Maintenance Costs	$7,133	$5,815	$5,042	$5,815
Battery Salvage Costs	--	($44)	($59)	($44)
Total Lifecycle Costs	$14,088	$14,087	$14,088	$13,734

[a] Battery module price at which life cycle parity with CV and HEV 0 occurs. This is equal to roughly 150,000 PHEV 20 packs per year (30,000 BEV packs) for the 2000 cycle PHEV and 45,000 PHEV 20 packs per year (12,000 BEV packs) for the 4000 cycle PHEV.

[b] EPRI HEVWG minimum battery price

Table 4-23
Net present value of life cycle costs over 10 years, 150,000 miles for SUV PHEV 20

Vehicle Type	**CV**	**PHEV 20**		
Battery Module Cost, $/kWh	--	$427[a]	$455[a]	$352[b]
Battery Size, kWh	--	9.30	11.00	9.30
Depth-of-discharge, % SOC	--	80%	70%	80%
Cycles to Failure Assumption	--	2,000	3,000	2,000
Incremental Vehicle Cost	--	$706	$706	$706
Energy Storage System Cost	$60	$6,072	$7,140	$5,375
Fuel Costs	$10,947	$5,608	$4,979	$5,608
Maintenance Costs	$7,113	$5,803	$5,374	$5,803
Battery Salvage Costs	--	($69)	($82)	($69)
Total Lifecycle Costs	$18,120	$18,120	$18,116	$17,422

[a] Battery module price at which life cycle parity with CV and HEV 0 occurs This is equal to roughly 84,000 PHEV 20 packs per year (26,000 BEV packs) for the 2000 cycle PHEV and 55,000 PHEV 20 packs per year (20,000 BEV packs) for the 3000 cycle PHEV.

[b] EPRI HEVWG minimum battery price

Life cycle cost parity for PHEV 20s versus HEV 0s and CVs can be met under several 10-year/150,000-mile scenarios. The higher battery cycle life scenarios[64] have lower life cycle costs. At the minimum battery price, the mid-size car PHEV 20 reduces the net present value of life cycle costs by $1,207 relative to the CV and the SUV PHEV 20 reduces the net present value of life cycle costs by $1,137. These reductions are largely due to larger fuel and maintenance savings. The 2000 cycle scenario also achieves life cycle cost parity and provides life cycle cost savings at minimum battery prices of $354 and $698 for the mid-size car and full-size SUV, respectively.

The prices used in the two mileage scenarios for HEV 0s do not include the estimated $1000 benefit the PHEV 20 brings to the carmaker in CAFE compliance benefits (See earlier subsection). As carmakers often pass on these benefits to consumers, this will dramatically reduce life cycle costs to the consumer. It is important to note that the high mileage drivers reach life cycle cost parity faster and this could be an important target market.

Life cycle cost parity for City EVs and PHEV 20s also improves the business case for battery leasing (called battery renting in Europe), where the consumer owns the car, but rents the battery. In Europe this has significantly increased sales of battery EVs[65]. The large advantage is the consumer no longer sees an upfront cost difference between the electric drive vehicle and its conventional counterpart.

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[64] 4000 cycles to failure for the mid-size car and 3000 cycles to failure for the SUV.

[65] Presentation by Marco Piffaretti at ETIC 2002 “Box-Energy: Project Description of the Energy Bank”

Increased production volumes are critical to reducing the costs hybrid-specific components for these vehicles. This study assumes that aggressive commercialization of hybrid electric vehicles by automakers (lead by Toyota and GM, making public statements regarding future production goals for hybrid vehicles) will drive down the costs of electric drive motors, power inverters, and other powertrain components. This study assumes that hybrids will be produced in significant volumes and that a mature electric drive industry will lower the price of hybrid system components closer to the bottom of their respective cost curves by end of this decade. This will significantly impact the life cycle cost of PHEVs.

A significant additional challenge is to lower the cost of PHEV "energy" batteries. As shown, above PHEV "energy" batteries do not need to get down to oft-stated goals of $150 per kWh or even the $235/kWh in the BTAP 2000 report [R-2].

When the USABC goals are translated into cost per mile goals, the PHEV 20s can more than met them. The USABC goal of $150 per kWh combined with a goal of a 150,000 mile vehicle translates into a goal of 2.24 cents per mile, assuming 0.25 kWh/mile vehicle efficiency[66] and this study's assumption of 2000 80% DOD cycles. Assuming 0.33 kWh/mile vehicle efficiency, this translates into a goal of 3.12 cents per mile.[67] The mid-size PHEV 20 with a 5.88 kWh pack at its estimated minimum cost of $320/kWh costs only 1.25 cents per mile.[68] The full-size SUV PHEV 20 with an 11 kWh pack at $352/kWh costs only 2.58 cents per mile[69]. These 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.

The retail price equivalent figures shown in this section contain dealer and manufacturer profits, which are substantial in the case of SUVs and luxury cars [R-12, R-13]. When the costs at the gate to the OEM are used, the cost differential for HEV 0s and PHEV 20s versus CV are much less. In fact a PHEV 20 mid-size car with a 2000 cycle battery is only $1,295 more than its HEV 0 counterpart. Table 4-24 below shows the incremental costs differences for the mid-size car, with the details in Appendix C. A PHEV 20 full-size SUV with a 2000 cycle battery is only $1,654 more than its HEV 0 counterpart as shown in Table 4-25.

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[66] ($150/kWh x 23.4 kWh pack using 80% DOD cycles and assuming 2000 cycles)/ 150,000 miles

[67] ($150/kWh x 31.2 kWh pack using 80% DOD cycles and assuming 2000 cycles)/ 150,000 miles

[68] ($320/kWh x 5.88 kWh pack)/150,000 miles

[69] ($352/kWh x 11 kWh pack)/150,000 miles

Table 4-24
OEM Cost at Gate comparisons for mid-size car

Vehicle Type	CV	HEV 0	PHEV 20	
Battery Module Cost $/kWh	—	$400	$320	$320
Battery Life, cycles	--	--	2,000	4,000
Battery Size, kWh	—	2.91	5.88	8.00
OEM Component Costs (less glider)	$3,682	$5,665	$6,960	$7,666
Incremental Cost at Gate vs CV	—	$1,983	$3,278	$3,984
Incremental cost at Gate vs HEV 0	—	—	$1,295	$2,001

Table 4-25
OEM Cost at Gate comparisons for SUV

Vehicle Type	CV	HEV 0	PHEV 20	
Battery Module Cost $/kWh	—	$400	$352	$352
Battery Life, cycles	--	--	2,000	3,000
Battery Size, kWh	—	5.19	9.30	11.00
OEM Component Costs (less glider)	$5,269	$8,827	$10,481	$11,102
Incremental Cost at Gate vs CV	—	$3,558	$5,212	$5,883
Incremental cost at Gate vs HEV 0	—	—	$1,654	$2,275

Consumers are also willing to pay higher prices for HEV 0s and PHEV 20s. Extensive collaborative market research was done by ARB, GM, Ford, DOE, SCAQMD, ANL, NREL, UCD, and utilities in the EPRI HEV Working Group [R-1, R-6]. The "Willingness to Pay" conclusions are shown in Table 4-26, below, with the details in Appendix C. Favorable customer response in not tied solely to the fuel economy improvements, but in the case of the PHEV 20s an additional set of benefits. These include less maintenance, reduced number of gas station fill-ups, convenience of having a full battery every morning, reduced air pollution, petroleum consumption and global warming as well as lower noise/vibration, improved acceleration, and features such as 120V appliances or pre-heat/pre-cool with the engine off [R-1].

Table 4-26
Willingness to pay from HEVWG Study [R-1, R-6]

Vehicle Platform	Vehicle Type	Willingness to Pay[a]
Mid-Size	HEV 0	$2,250
	PHEV 20	$3,600
SUV	HEV 0	$3,000
	PHEV 20	$5,500

[a] Amount consumers of new vehicles indicated they are willing to pay for benefits of HEVs and PHEVs above the CV price

5

LIFE CYCLE COSTS FOR CITY ELECTRIC VEHICLES

Introduction

This section uses the life cycle cost model discussed in Section 4 to examine City EVs. The ARB in its August 7, 2000 staff report [R-5] analyzed City EV life cycle cost over a 10-year, 87,000-mile scenario. This section updates that model with a City EV designed using cost data from the EPRI HEVWG [R-1, R-6] studies. For this report, the ARB model was expanded to include a 110,000 mile 10-year scenario. This section carefully compares the prior ARB model and this study's enhanced model for City EVs.

As described in the previous sections, NiMH battery life can be extended to last 10 years, 150,000 miles, potentially eliminating the need for battery replacements. Eliminating mandatory battery replacements during the nominal vehicle life reduces the life cycle cost of battery electric vehicles (BEVs) substantially. The analysis time frame was set in later part of this decade in order to answer key questions: Given that millions of power assist HEVs are anticipated to reach the market by the end of the decade, worldwide,[70] and given that this mass production will lower the cost of key electric drive components (e.g. drive motors, power inverters, etc.), how will this benefit city EVs? Is life cycle cost parity with conventional gasoline-powered city cars possible? If so, what annual production volume of plug-in HEV batteries[71] or city EV batteries is needed in order to reach life cycle cost parity? Data supporting the charts and tables in this section can be found in Appendix B.

Vehicle Designs and Platforms

Two vehicle designs are compared and contrasted in this section. The two vehicle designs are:

- A conventional vehicle (CV) with an internal-combustion engine (ICE) that served as baseline for the comparisons of vehicle attributes
- A battery electric vehicle with a battery of sufficient capacity to provide about 40 miles of all-electric range (BEV 40)

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[70] Based upon the fact that all the major manufacturers are either building or are planning to build hybrid electric vehicles such that production of key components will reach the hundreds of thousands per year (possibly millions per year) in the later part of this decade. See Section 4 for details.

[71] A plausible scenario is that plug-in NiMH HEV batteries, which have more specific power and less specific energy than the best BEV NiMH batteries, are mass-produced while high energy NiMH BEV batteries for city EVs are not. This chapter assumes this scenario, but recognizes that PbA, NiCd, ZEBRA, and lithium batteries are also feasible candidates for City EVs.

Life Cycle Cost Methodology

- BEVs were examined using an improved version of the California Air Resources Board (ARB) life cycle cost model. The EPRI life cycle model discussed in Section 4 compares vehicles based upon purchase price, fuel costs and maintenance costs. The model included assumptions on incremental purchase price, battery initial and replacement costs, battery life, maintenance costs and fuel costs. Annual costs are inflated over time using an inflation rate of 3 percent. To bring future costs to current 2003 dollars, a discount rate of 8 percent is used to calculate the net present value of future costs. Fuel costs used are $1.75 per gallon for gasoline and $0.05 per kWh for electricity. The low electricity cost is based upon off-peak charging. Changes in this study's methodology from the 2000 ARB Staff Report life cycle model (ARB Model) are discussed in the following subsections along with how they affect the life cycle costs.

Incremental Vehicle Costs

Incremental vehicle costs in this study were calculated using a cost based price method developed by Argonne National Laboratory (ANL) for the Hybrid Electric Vehicle Working Group (HEVWG). This method is detailed in the 2001 EPRI HEV report *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* (EPRI report 1000349). In the ANL method, electric components (motor, power inverter, battery, etc.) are assumed to be supplied by outside vendors. Their costs include not only the cost of labor and materials, but also a partial mark-up that includes some research and development costs, supplier overhead and profit, and appropriate warranties. Different mark-ups are applied to component costs depending on whether they are built by the manufacturer or supplied by a supplier. A single mark-up covers manufacturer and dealer mark-ups and development costs.

As discussed in the previous Section 4, projected costs of brushless permanent magnet (BPM) motors and motor controllers are significantly lower if the permanent magnets and IGBTs are used in other applications such as engine dominant HEVs. When this occurs, projected vehicle costs will be substantially reduced. We assume these cost reductions will happen by 2013. Total vehicle prices (cost based price using the ANL method) using ARB's battery module cost of $300 per kWh are shown in Table 5-1. This incremental price calculated here is less than half of the incremental price for Vehicle 15 in the 2000 ARB Staff Report ($10,058). This substantial reduction is mostly due to the reduction in costs of electric traction motors and controllers due to volume production of these items from HEV sales and provides a $5,780 savings in life cycle costs over ARB's analysis.

Table 5-1
Vehicle prices using the ANL cost-based price method

Specifications	CV	BEV 40
Engine Power, kW	36	--
Engine Type	I-3	--
Traction motor, kW	--	27
Battery Size, kWh		9.1
Glider	$7,799	$7,799
Engine + Exhaust	$2,129	$0
Transmission	$1,600	$1,000
Accessory Power	$352	$462
Electric Traction	$60	$1,519
Energy Storage System	$60	$4,807
On Vehicle Charging System	—	$690
Total Price less Battery	$12,000	$16,278
Incremental Price	--	$4,278

Lifetime Mileage Assumptions

Two mileage accumulation schedules were used in the EPRI model. The low mileage schedule was that used in the 2000 ARB Staff Report for city EVs. The high mileage schedule was defined at 25 percent higher mileage. These schedules are shown in Table 5-2.

Table 5-2
Annual Mileage Accumulation Rates for life cycle costs

Year	Mileage Assumption	
	Low	High
1	10,014	12,518
2	9,711	12,139
3	9,417	11,771
4	9,132	11,415
5	8,856	11,070
6	8,588	10,735
7	8,328	10,410
8	8,076	10,095
9	7,832	9,790
10	7,595	9,494
Total	87,549	109,436

Battery Life Assumptions

In the 2000 ARB Staff Report, ARB assumed that near-term NiMH batteries would only last approximately 6 years or 50,000 miles in deep discharge use. As stated in Section 3, SCE has seen several RAV4s with NiMH batteries have over 100,000 miles of use without battery replacement. Based on this as well as laboratory tests discussed in Chapter 3, it is expected that batteries will last for 150,000 miles or 10 years whichever comes first by middle part of this decade. In deep discharge operation (80% DOD), these batteries will last 2,000 cycles. At 70% DOD, it is expected that these batteries will last 3,000 cycles. Table 5-3 shows the assumptions used in this report on battery life.

Table 5-3
NiMH Battery Life Assumptions

Assumption	Low Mileage	High Mileage
Battery Size, kWh	9.0	9.5
Discharge %	80%	70%
Lifetime Discharge Cycles	2,000	3,000
Miles per Charge	44	41
Maximum Battery Electric Miles	87,805	121,646
Assumed Battery Electric Miles	87,549	109,436

- By providing batteries that last through the lifetime of the vehicle, battery replacement costs are no longer part of the analysis. In the Vehicle 15 example of the 2000 ARB Staff Report, this reduces the net present value of life cycle costs by $2,047 in addition to the $5,780 savings in life cycle costs discussed earlier. ARB's Vehicle 19 (volume production city EV) shows batteries lasting 10 years.
- The increased battery sizes listed in Table 5-3, however, reduce the cost of the vehicle by $32 for the low mileage case and increase it by $128 in the high mileage case.

Battery Salvage Value

In the 2000 ARB Staff Report, battery salvage value was set at $40 per kWh. In the EPRI model, battery salvage value was set at the battery module costs (for new modules) at time of salvage times the percent of life left on the battery times the original battery capacity. In the low mileage case, the battery salvage value was only $1 per kWh and the high mileage case was $27 per kWh. This increased the net present value of life cycle costs by $357 for the low mileage case and $53 for the high mileage case.

Fuel Economy Estimates

In the 2000 ARB Staff Report, BEVs were shown to have an urban fuel economy of 0.25 kWh per mile for the 2003 case (Vehicle 15) and 0.18 kWh per mile for the volume case. Since the vehicles modeled in the EPRI model are those in existence in 2012, a fuel economy of 0.2 kWh per mile was used. Tests done on current city cars or small commuter cars at Southern California Edison show fuel economies below 0.2 kWh per mile.[72] Net present value of fuel costs over the low mileage case was $669 compared with ARB's value of $836 for vehicle 15 with a fuel economy of 0.25 kWh per mile. The high mileage case had a net present value of fuel costs of $836.

Improved Maintenance Assumptions

The original ARB Model used extremely simplified maintenance assumptions that only provided average cents per mile for each technology. These assumptions are given in Table 5-4 for CVs, HEVs, and battery electric vehicles (BEVs).

Table 5-4
ARB Maintenance Estimates (cents per mile)

Vehicle Type	Maintenance costs
CV	6.0¢ per mile
Freeway BEV	4.0¢ per mile
City BEV	3.5¢ per mile

Conventional vehicle maintenance costs were calculated using data from the Automobile Club of Southern California. The 2000 ARB Staff Report claims that the 6 cents per mile includes approximately 4.3 cents of estimated maintenance expenses, and 1.7 cents per mile of tire expenses. The reduced BEV costs were based upon maintenance cost experiences from utility company fleets. Maintenance costs for BEVs were assumed to be one-third less than CV maintenance costs, which includes increased tire costs for low rolling resistance tires used on BEVs. This is consistent with reduced maintenance requirements found by SCE and discussed in Section 4. If the increased tire costs were assumed to be one third more per mile than the CV tire costs, non tire maintenance costs for BEVs would be 1.7 cents per mile versus 4.3 cents or roughly 60% less (and 1.2 cents per mile versus 4.3 cents per mile or roughly 72% less for the City EVs in the ARB model).

As described in Section 4, the EPRI model uses detailed maintenance assumptions based upon scheduled engine maintenance. Maintenance costs (parts and labor) and frequency are given in Table 5-5 for city cars[73]. (See Section 4 for a more detailed discussion on maintenance, which indicates the conservative nature of these assumptions).

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[72] Personal communication with Dean Taylor and Michel Wehrey of Southern California Edison based on SCE's testing of five cars on an urban driving test, called the Pomona loop.

[73] Maintenance costs and frequency were taken from www.edmunds.com. City car maintenance costs were for a 2003 Toyota Echo.

Table 5-5
Schedule Maintenance Costs for City Cars

Item	Frequency[a]	CV
Engine Oil	5,000	$23.69
Oil Filter	5,000	$12.92
Fuel filter	15,000	$35.50
Air Filter	30,000	$27.88
Spark plugs	30,000	$44.65
Timing Belt Replacement	60,000	$260.00
PCV valve	100,000	$18.54
Front Brake Pads	30,000/60,000[b]	$204.00
Front Brake Rotors	60,000/120,000[c]	$270.00

[a] Based on IC engine miles

[b] Front brake pads replaced every 30,000 vehicle miles for CVs, every 60,000 vehicle miles for HEVs

[c] Front brake rotors replaced every 60,000 vehicle miles for CVs, every 120,000 vehicle miles for HEVs.

In addition, a fixed maintenance cost for other engine related inspections was set at 0.2 cents per mile. Non-engine related maintenance that would be common between BEVs and CVs was set at 1.4 cents per vehicle mile. Tire maintenance is set at 1.7 cents per mile for both BEVs and CVs because by 2012, CVs and BEVs will likely be using the same tires. Incremental net present value of maintenance costs between the BEV 40 and the CV are $1,741 for the low mileage case and $2,442 for the high mileage case. This is about the same as ARB's estimate of $1,672 for the low mileage case.

Overall Assumption Changes

The effect of changes to the ARB model on incremental net present values of life cycle costs between a city CV and a city BEV 40 are shown in Table 5-6 for the low mileage case. Each of these changes represents an improvement in the model. The key improvements are in the first two rows and are due to today's NiMH batteries lasting longer, and the key study assumption that by the end of this decade, HEV 0s will have reduced the price of hybrid system components to near the bottom of their cost curve. Battery module prices were assumed the same as ARB in Table 5-6, i.e., $300/kWh.

Table 5-6
Effect of Changes to ARB's Model for the Low Mileage Case (Net Present Value)

Assumption	ARB's Model[a]	EPRI's Model
Incremental Vehicle Cost	$9,558	$4,246
Battery Life Assumption[b]	$2,047	$0
Battery Salvage Value	($701)	($4)
Fuel Economy	$2,090[c]	$1,932[d]
Maintenance	$1,672	$1,741
Range Assumption	36 miles	40 miles
Battery size (kWh)	9.1	9.0

[a] Comparison of Vehicle 25 for the CV and Vehicle 15 for the BEV

[b] ARB assumed that the battery would need replacement in the sixth year of operation at a cost of $3,248. EPRI assumes the battery will last 10 years and 87,800 miles.

[c] Fuel economy assumptions for ARB model: CV 40 mpg, BEV 0.25 kWh/mi, gasoline price $1.75 per gallon, electricity price $0.05 per kWh, 87,549 lifetime miles.

[d] Fuel economy assumptions for EPRI model: CV 45 mpg, BEV 0.20 kWh/mi, gasoline price $1.75 per gallon, electricity price $0.05 per kWh, 87,549 lifetime miles. ARB also had future high volume case had CV at 45 mpg and 0.18 kWh/mi

Overall Results and Conclusions

Using a battery module cost of $300 per kWh, the net present value of life cycle costs for both the CV and the BEV 40 are given in Table 5-7 for both the low and high mileage cases. Even at $300 per kWh, the BEV 40 is more cost effective on a net present life cycle basis than the CV in the high mileage case. In fact, net present value of life cycle costs in the high mileage case is met with battery module costs of $364 per kWh with the given assumptions[74] of this study. With increased use of batteries for HEVs and PHEVs between now and later part of this decade, PHEV NiMH battery prices should drop below $360 per kWh and make City EVs cost effective. This is equivalent to producing roughly 47,000 BEV 40 packs[75] or 71,000 PHEV 20 packs (14,000 full-size EV battery packs) per year at $364 per kWh[76] based upon Figure 3-2, Figure 3-3, and Figure 4-1. While utilizing PHEV 20 batteries in a BEV 40 results in somewhat higher battery costs (due to a higher than necessary power-to-energy ratio), the advantage of some level of battery commonality can reduce battery costs for both vehicle types.

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[74] Cost-based pricing (ignoring tax breaks, CAFE benefits internal to the carmaker, or other factors), inflation, discount rate, electricity and gasoline price, maintenance, fuel economy and battery life, second use value, split of off-board electric vs gasoline-powered miles, cost of hybrid system components

[75] This assumption is based on the City BEV using the same NiMH battery module design as a PHEV, so both vehicles would benefit from increased production volume of either vehicle.

[76] Using a direct ratio of energy storage capacity and the conservative assumption for effect of production volume on battery pricing, 14,000 fullsize EV battery packs are equivalent to approximately 70,000 PHEV 20 battery packs (6 kWh) or 45,000 BEV 40 battery packs (9-9.5 kWh)

The prices used in this scenario do not include the estimated $2,000 benefit the City EV brings to the carmaker in CAFE compliance benefits (See detailed discussion in Section 4). As carmakers often pass on these benefits to consumers, life cycle costs will be substantially reduced, so that even low mileage cases can reach life cycle cost parity.

Table 5-7
Net present value of life cycle costs over 10 years for City Cars

Mileage Assumption	**Low**		**High**	
Vehicle	**CV**	**BEV 40**	**CV**	**BEV 40**
Total Vehicle Cost	$12,000	$16,246	$12,000	$16,406
Battery Salvage Costs	--	($4)	--	($133)
Fuel Costs	$2,601	$669	$3,252	$836
Maintenance Costs	$4,138	$2,216	$5,201	$2,741
Life Cycle Costs	$18,739	$19,127	$20,452	$19,850

There are many other battery chemistries suitable for City EVs instead of the PHEV-type NiMH batteries used in this study. Lithium ion, nickel cadmium, sodium nickel chloride[77], lithium polymer, lead acid, and EV-type NiMH are capable of meeting many, and possibly all of the design constraints of city electric vehicles[78]. Many of these battery chemistries have at least the potential (given sufficient production volume) to match or surpass the cost-effectiveness of for PHEV-type batteries[79]. For example, EV-type NiMH in volume production can reach $235/kwh, which would reduce the up-front price of the BEV 40 by about $600. Investigation of some of these alternate battery scenarios could result in a lower life cycle cost path for City EVs.

Life cycle cost parity for City EVs and PHEV 20s also improves the business case for battery leasing (called battery renting in Europe), where the consumer owns the car, but rents the battery. In Europe this has significantly increased sales of battery EVs. Battery leasing largely removes the upfront cost difference between the electric drive vehicle and its conventional counterpart. This has proven to increase the customer preference for EVs in targeted European markets[80].

The most important reason for the improved numbers in this study's enhanced version of the ARB model is the reduction in costs of electric traction motors and controllers due to volume production of these items from HEV 0 sales. This provides a $5,780 savings in life cycle costs over ARB's analysis (with other variables held constant).

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[77] Sodium nickel chloride batteries are manufactured under the brand name "ZEBRA" by MES of Mendrissio, Switzerland.

[78] This does not imply that all of these battery chemistries are verifiable replacements, especially when considering durability and calendar life in a specific application. The City EV category is diverse in nature, and the energy storage system requirements are highly specific to each vehicle. In general, these battery chemistries have either been applied to prototype or production City EVs or are judged to be likely candidates for these vehicles.

[79] The bottom of the cost curve for PHEV-type NiMH batteries is projected at roughly $300/kWh.

[80] Presentation by Marco Piffaretti at ETIC 2002 "Box-Energy: Project Description of the Energy Bank"

While ARB found that City EVs could reach life cycle cost parity in high volume production with battery module cost at $235/kWh, this study finds that City EVs (using a more sophisticated variation on the ARB model) can reach life cycle cost parity at $364/kWh, in low volume production of approximately 45,000 City BEV NiMH battery packs or 70,000 mid-size PHEV 20 NiMH battery packs per year in the later part of this decade. The key assumptions are the reduction in electric-drive component costs due to expected volume production of power assist hybrids, battery commonality with other vehicles (e.g. PHEV 20), and longer life NiMH battery technology. Pricing strategies that take into account the CAFE benefits or a carmaker's interest in capturing new markets or creating a new image are not considered, but would probably improve the results. Battery leasing (owning the car, but leasing the batteries) is another possible method to capitalize on the life cycle cost benefits shown in this section.

6

COST-EFFECTIVENESS OF HEVS, PHEVS, AND CITY EVS IN REDUCING POLLUTION, PETROLEUM CONSUMPTION, AND GREENHOUSE GASES

Introduction

Cost-effectiveness in this study is examined from the consumer or societal perspective. "Cost-effectiveness is a measure of the cost incurred to achieve a specific outcome, as compared to other ways to reach that same end," according to ARB staff.[81]

In considering cost-effectiveness to the consumer, if the long-term or life cycle costs[82]of two technologies are the same, then the one with the larger reductions in smog-forming gases, greenhouse gases, water pollution and petroleum is the preferred technology for society. When consumer life cycle cost parity is reached, society is achieving these imporant benefits for no cost. In technical terms, the cost-effectiveness of reducing pollution, petroluem and global warming gases is $0/ton of gases removed. This type of analysis is useful in examining several alternative fuel vehicles, such as electricity, natural gas, and hydrogen powered vehicles, which have large maintenance and fuel savings benefits that can offset the higher upfront costs of these emerging technologies in the eyes of the consumer.

ARB January 10, 2003 Staff report

It is helpful to remember the perspective in the ARB staff report [R-8].

"*The ZEV program has always combine two distinct objectives – first, achieving emission reductions today through expanded introduction of commercially available near zero-emission technology, and second, accelerating the development of pure ZEV technologies that have the potential to provide significant air quality benefits over the long term, but have minimal immediate air quality impact given their pre-commercial status and limited production. … The second objective of the program is to accelerate the development of pure ZEV technology to*

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[81] Reference 8, page 58.

[82] Life cycle costs in this study is a simplified version which includes the net present value of the scheduled maintenance costs (no repair costs) and the fuel costs as well as the incremental retail price equivalent (using the ANL cost-based price method) with no use of tax breaks, internal cross-product line subsidies, reduction in profits, or other pricing factors. See sections 4 and 5 for details.

achieve significant future air quality benefits. This is accomplished by the pure ZEV obligation within the program.

In proposing amendments to the regulation in 2001, ARB staff provided data to the Board that showed that in the early years of the ZEV program the dollars spent per ton of pollutant reduced would be much higher than for any other ARB regulatory measure. The Board, however, voted unanimously to maintain the program because of its belief that the ZEV program needs to be viewed and considered on a long-term basis. Simply put, the Board has expressed confidence in the technical capacity of industry to reduce cost such that the long-term costs of ZEVs will be comparable to conventional vehicles."

It is worth noting that the Board not only voted in January 2001 to maintain the ZEV program, but also directed staff to nearly double the volumes of ZEVs and AT PZEVs in the staff proposal by 2012 in order to achieve high volume production that is key to reducing costs. This substantial increase in the program was intended to help it become more cost-effective. In addition, the Board heard from many EV owners and others about the many benefits of EVs (e.g. lower operating costs, conveniences, performance benefits, etc) which factor into their purchase decision. The consumer perspective on ZEV cost was certainly heard.

The ARB staff report [R-8] emission reductions for various technologies are listed in Table 6-1. The PHEV 20 emission numbers in Table 6-1 are based on their numbers of lifetime ZEV miles in Appendix A and B.

Table 6-1
Emission reductions for SULEVs, PZEVs, HEV 0s, PHEV 20s, and City EVs

Vehicle Type	NMOG (g/mile)	NOx (g/mile)	117,000 mile ROG+NOx (pounds)	150,000 mile ROG+NOx (pounds)	Benefit vs. SULEV / 0.5 evap (pounds)
SULEV / 0.5 evap	0.0703	0.0266	24.99	32.04	0.00
PZEV	0.0577	0.0256	21.49	27.55	4.49
AT PZEV HEV 0	0.0477	0.0251	18.78	24.07	7.97
Mid-size PHEV 20 (low mile version)	0.0321	0.0169	12.64	N/A	12.35
Mid-size PHEV 20 (high mile version)	0.0228	0.0120	N/A	11.51	20.53
Full-size SUV PHEV 20 low mile	0.0314	0.0165	12.36	N/A	12.63
Full-size SUV PHEV 20 (high mile version)	0.0280	0.0147	N/A	14.12	17.92
City EV	0.002	0.0003	0.59	N/A	24.40

Life Cycle Cost to Consumer

Based upon the life cycle analyses in Section 4, cost parity with CVs are possible for mid-size HEV 0s and PHEV 20s at fairly low production volumes. Cost parity for SUV HEV 0s and PHEV 20s can be met when considering the life cycle cost over 10 years/150,000 miles. At cost parity, the cost per ton of emissions reduced is $0 per ton. City BEV 40s can also show cost parity for the 10-year/110,000 mile case. Again at cost parity, cost-effectiveness is $0 per ton of emissions reduced. Table 6-2 shows cost effectiveness versus incremental life cycle cost to the consumer for mid-size HEV 0s and PHEV 20s.

Table 6-3 shows cost effectiveness versus incremental life cycle cost to the consumer for SUV HEV 0s and PHEV 20s. Table 6-4 shows cost effectiveness versus incremental life cycle costs to the consumer for City BEV 40s.

The most recent ARB staff report [R-8] list the cost-effectiveness of ZEVs only based on the fuel cell cost estimates on page 60. In 2012 and later, ARB staff projects fuel cell EVs with an incremental cost of $10,000 will have a cost-effectiveness of $639,795 per ton of NOx and ROG removed. Staff puts this high number in context by explaining:

"Clearly the dollars per ton estimates given above greatly exceed those for other air pollution control measures. They must, however, be viewed in context of the objective that the Board is trying to achieve. The purpose of the pure ZEV obligation within the ZEV program is to maintain significant pressure on manufacturers to continue ZEV technology development. Staff knows of no other mechanism that can accomplish this objective in a more economical fashion. In addition, staff expects that the long-term cost of ZEV technology will decline beyond the cost estimates shown here."

This study is suggesting a more economical way to reduce ZEV costs. Table 6-2, Table 6-3, and Table 6-4 show that PHEV 20s and City EVs with 40 miles range can even provide substantial benefits at no cost as even as battery prices are much higher than the bottom of the battery cost / volume curve. Achieving zero dollars per ton of emission reductions is difficult to do, but the ZEV program later in this decade can achieve this. Many ARB and local air district programs have cost effectiveness in the range of $10,000 to 20,000 per ton of pollution removed.

Table 6-2
Cost-effectiveness to the consumer for mid-size HEV 0s and PHEV 20s

Vehicle Type	**HEV 0**	**PHEV 20**			
Battery Module Cost $/kWh	$400	$480	$400	$320	$320
Mileage Assumption	High	High	High	High	Low
Emission Reduction (lifetime lbs)	7.97	20.53	20.53	20.53	12.35
Incremental Lifecycle costs	($500)	$91	($549)	($1,189)	$24
Cost-Effectiveness ($/ton)	($125,471)	$8,865	($53,483)	($115,830)	$3,887

Table 6-3
Cost-effectiveness to the consumer for SUV HEV 0s and PHEV 20s

Vehicle Type	HEV 0	PHEV 20			
Battery Module Cost $/kWh	$400	$480	$400	$352	$352
Mileage Assumption	Both	High	High	High	Low
Emission Reduction (lifetime lbs)	7.97	17.92	17.92	17.92	12.63
Incremental Lifecycle costs	($97)	$288	($592)	($1,120)	$141
Cost-Effectiveness ($/ton)	($24,341)	$32,143	($66,071)	($125,000)	$22,328

Table 6-4
Cost-effectiveness to the consumer for City BEV 40s

Vehicle Type	BEV 40		
Battery Module Cost $/kWh	$400	$320	$320
Mileage Assumption	High	High	Low
Emission Reduction (lifetime lbs)	22.94	22.94	18.25
Incremental Lifecycle costs	$372	($388)	$749
Cost-Effectiveness ($/ton)	$32,432	($33,827)	$82,082

A
HEV AND PHEV LIFE CYCLE COSTS

Table A-1 gives the maximum cost to manufacturer allowable for HEVs and PHEVs to reach life cycle cost parity with the CV for the mid-size vehicle. These costs are assumed to occur in early production levels.

Table A-2 gives the cost to manufacturer for HEVs and PHEVs at minimum battery prices expected in large production for the mid-size vehicle.

Table A-3 gives the maximum cost to manufacturer allowable for HEVs and PHEVs to reach life cycle cost parity with the CV for full-size SUVs. These costs are assumed to occur in early production levels.

Table A-4 gives the cost to manufacturer for HEVs and PHEVs at minimum battery prices expected in large production for full-size SUVs.

Table A-5 gives the maximum vehicle price to consumers for HEVs and PHEVs to have life cycle cost parity with the CV for mid-size cars. This uses the ANL method to calculate a cost based price. Table A-6 gives mid-size vehicle prices at volume production.

Table A-7 gives the maximum vehicle price to consumers for HEVs and PHEVs to have life cycle cost parity with the CV for SUVs. This uses the ANL method to calculate a cost based price. Table A-8 gives SUV prices at volume production.

Maintenance costs are shown in Table A-9 for the mid-size CV, Table A-10 for the mid-size HEV 0, and Table A-11 for the mid-size PHEV 20. Maintenance costs for SUVs are shown in Table A-12 for the CV, Table A-13 for the HEV 0 and Table A-14 for the PHEV 20.

Net present value of life cycle cost calculations are shown in Table A-15 through Table A-36.

Table A-1
Mid-size vehicle costs to manufacturer at life cycle cost parity

Vehicle Type	**CV**	**HEV 0**		**PHEV 20**		
Mileage Assumption	**Both**	**Low**	**High**	**Low**	**High**	**High**
Engine Power, kW	127	67	67	61	61	61
Engine Configuration	V-6	I-4	I-4	I-4	I-4	I-4
Traction motor Power, kW peak	N/A	44.3	44.3	51.3	51.3	51.3
Battery Energy, kWh	N/A	2.91	2.91	5.88	5.88	8.00
Battery Module Costs, $/kWh	N/A	385	572	316	380	471
Engine	2077	1228	1228	1156	1156	1156
Engine Thermal	30	16	16	14	14	14
Engine Total	**2107**	**1244**	**1244**	**1170**	**1170**	**1170**
Exhaust System	**250**	**200**	**200**	**200**	**200**	**200**
Transmission	**1045**	**625**	**625**	**625**	**625**	**625**
Power Steering Pump	50	50	50	50	50	50
Generator/Alternator	40					
A/C Compressor	100	100	100	100	100	100
A/C Condenser	20	20	20	20	20	20
APM	0	130	130	130	130	130
Accessory Power Total	**210**	**300**	**300**	**300**	**300**	**300**
Starter Motor	40					
Electric Motor		797	797	893	893	893
Power Inverter		478	478	528	528	528
Electronics Thermal		114	114	121	121	121
Electric Traction Total	**40**	**1390**	**1390**	**1542**	**1542**	**1542**
Fuel Storage (tank)	10	10	10	10	10	10
Accessory Battery	20	15	15	15	15	15
Energy Batteries		1120	1665	1858	2234	3768
Pack Tray		145	145	159	159	170
Pack Hardware		475	475	489	489	500
Battery Thermal		99	99	108	108	114
Energy Storage Total	**30**	**1863**	**2407**	**2640**	**3016**	**4577**
Charger				380	380	380
Cable				80	80	80
Charging Total	**0**	**0**	**0**	**460**	**460**	**460**
Total	**3682**	**5622**	**6166**	**6937**	**7313**	**8874**
Incremental		1939	2484	3255	3631	5192

Table A-2
Mid-size vehicle costs to manufacturer at volume production

Vehicle Type	**CV**	**HEV 0**	**PHEV 20**	
Mileage Assumption	**Both**	**Both**	**Both**	**High**
Engine Power, kW	127	67	61	61
Engine Configuration	V-6	I-4	I-4	I-4
Traction motor Power, kW peak	N/A	44.3	51.3	51.3
Battery Energy, kWh	N/A	2.91	5.88	8.00
Battery Module Costs, $/kWh	N/A	400	320	320
Engine	2077	1228	1156	1156
Engine Thermal	30	16	14	14
Engine Total	**2107**	**1244**	**1170**	**1170**
Exhaust System	**250**	**200**	**200**	**200**
Transmission	**1045**	**625**	**625**	**625**
Power Steering Pump	50	50	50	50
Generator/Alternator	40			
A/C Compressor	100	100	100	100
A/C Condenser	20	20	20	20
APM	0	130	130	130
Accessory Power Total	**210**	**300**	**300**	**300**
Starter Motor	40			
Electric Motor		797	893	893
Power Inverter		478	528	528
Electronics Thermal		114	121	121
Electric Traction Total	**40**	**1390**	**1542**	**1542**
Fuel Storage (tank)	10	10	10	10
Accessory Battery	20	15	15	15
Energy Batteries		1164	1882	2560
Pack Tray		145	159	170
Pack Hardware		475	489	500
Battery Thermal		99	108	114
Energy Storage Total	**30**	**1907**	**2663**	**3369**
Charger			380	380
Cable			80	80
Charging Total	**0**	**0**	**460**	**460**
Total	**3682**	**5665**	**6960**	**7666**
Incremental		1983	3278	3984

Table A-3
SUV costs to manufacturer at life cycle cost parity

Vehicle Type	**CV**	**HEV 0**		**PHEV 20**		
Mileage Assumption	**Both**	**Low**	**High**	**Low**	**High**	**High**
Engine Power, kW	212	145	145	115	115	115
Engine Configuration	V-8	V-8	V-8	V-6	V-6	V-6
Traction motor Power, kW peak	N/A	65.3	65.3	98.0	98.0	98.0
Battery Energy, kWh	N/A	5.19	5.19	9.30	9.30	11.00
Battery Module Costs, $/kWh	N/A	255	419	337	427	455
Engine	3395	2658	2658	1947	1947	1947
Engine Thermal	50	34	34	27	27	27
Engine Total	**3445**	**2692**	**2692**	**1974**	**1974**	**1974**
Exhaust System	**300**	**300**	**300**	**300**	**250**	**250**
Transmission	**1200**	**800**	**800**	**800**	**800**	**800**
Power Steering Pump	55	55	55	55	55	55
Generator/Alternator	45					
A/C Compressor	120	120	120	120	120	120
A/C Condenser	24	24	24	24	24	24
APM	0	140	140	140	140	140
Accessory Power Total	**244**	**339**	**339**	**339**	**339**	**339**
Starter Motor	50					
Electric Motor		1085	1085	1533	1533	1533
Power Inverter		627	627	858	858	858
Electronics Thermal		135	135	168	168	168
Electric Traction Total	**50**	**1847**	**1847**	**1847**	**2559**	**2559**
Fuel Storage (tank)	10	10	10	10	10	10
Accessory Battery	20	15	15	15	15	15
Energy Batteries		1323	2175	3134	3971	5005
Pack Tray		156	156	177	177	185
Pack Hardware		486	486	507	507	515
Battery Thermal		106	106	118	118	123
Energy Storage Total	**30**	**2096**	**2947**	**3960**	**4797**	**5853**
Charger				380	380	380
Cable				80	80	80
Charging Total	**0**	**0**	**0**	**0**	**460**	**460**
Total	**5269**	**8074**	**8925**	**10342**	**11179**	**12235**
Incremental		2805	3656	5073	5910	6966

Table A-4
SUV costs to manufacturer at volume production

Vehicle Type	**CV**	**HEV 0**	**PHEV 20**	
Mileage Assumption	**Both**	**Both**	**Both**	**High**
Engine Power, kW	212	145	115	115
Engine Configuration	V-8	V-8	V-6	V-6
Traction motor Power, kW peak	N/A	65.3	98.0	98.0
Battery Energy, kWh	N/A	5.19	9.30	11.00
Battery Module Costs, $/kWh	N/A	402	352	352
Engine	3395	2658	1947	1947
Engine Thermal	50	34	27	27
Engine Total	**3445**	**2692**	**1974**	**1974**
Exhaust System	**300**	**300**	**250**	**250**
Transmission	**1200**	**800**	**800**	**800**
Power Steering Pump	55	55	55	55
Generator/Alternator	45			
A/C Compressor	120	120	120	120
A/C Condenser	24	24	24	24
APM	0	140	140	140
Accessory Power Total	**244**	**339**	**339**	**339**
Starter Motor	50			
Electric Motor		1085	1533	1533
Power Inverter		627	858	858
Electronics Thermal		135	168	168
Electric Traction Total	**50**	**1847**	**2559**	**2559**
Fuel Storage (tank)	10	10	10	10
Accessory Battery	20	15	15	15
Energy Batteries		2086	3274	3872
Pack Tray		156	177	185
Pack Hardware		486	507	515
Battery Thermal		106	118	123
Energy Storage Total	**30**	**2859**	**4100**	**4720**
Charger			380	380
Cable			80	80
Charging Total	**0**	**0**	**460**	**460**
Total	**5269**	**8837**	**10481**	**11102**
Incremental		3568	5212	5833

Table A-5
Mid-size vehicle prices using ANL method at life cycle cost parity

Vehicle Type	**CV**	**HEV 0**		**PHEV 20**		
Mileage Assumption	**Both**	**Low**	**High**	**Low**	**High**	**High**
Engine Power, kW	127	67	67	61	61	61
Engine Configuration	V-6	I-4	I-4	I-4	I-4	I-4
Traction motor Power, kW peak	N/A	44.3	44.3	51.3	51.3	51.3
Battery Energy, kWh	N/A	2.91	2.91	5.88	5.88	8.00
Battery Module Costs, $/kWh	N/A	$385	$572	$316	$380	$471
Glider	$11,525	$11,525	$11,525	$11,525	$11,525	$11,525
Engine + Exhaust	$4,715	$2,888	$2,888	$2,741	$2,741	$2,741
Transmission	$2,090	$1,250	$1,250	$1,250	$1,250	$1,250
Accessory Power	$420	$535	$535	$535	$535	$535
Electric Traction	$80	$2,084	$2,084	$2,313	$2,313	$2,313
Energy Storage System (ESS)	$60	$3,047	$3,591	$3,893	$4,269	$5,844
On Vehicle Charging System	—	—	—	$690	$690	$690
Total Price	$18,890	$21,329	$21,873	$22,947	$23,323	$24,898
Incremental Price	—	$2,440	$2,984	$4,057	$4,433	$6,008
Incremental Price less ESS	—	($547)	($547)	$224	$224	$224

Table A-6
Mid-size vehicle prices using ANL method at volume production

Vehicle Type	**CV**	**HEV 0**	**PHEV 20**	
Mileage Assumption	**Both**	**Both**	**Both**	**High**
Engine Power, kW	127	67	61	61
Engine Configuration	V-6	I-4	I-4	I-4
Traction motor Power, kW peak	N/A	44.3	51.3	51.3
Battery Energy, kWh	N/A	2.91	5.88	8.00
Battery Module Costs, $/kWh	N/A	$400	$320	$320
Glider	$11,525	$11,525	$11,525	$11,525
Engine + Exhaust	$4,715	$2,888	$2,741	$2,741
Transmission	$2,090	$1,250	$1,250	$1,250
Accessory Power	$420	$535	$535	$535
Electric Traction	$80	$2,084	$2,313	$2,313
Energy Storage System (ESS)	$60	$3,091	$3,916	$4,636
On Vehicle Charging System	—	—	$690	$690
Total Price	$18,890	$21,373	$22,970	$23,690
Incremental Price	—	$2,483	$4,081	$4,800
Incremental Price less ESS	—	($547)	$224	$224

Table A-7
SUV prices using ANL method at life cycle cost parity

Vehicle Type	CV	HEV 0		PHEV 20		
Mileage Assumption	**Both**	**Low**	**High**	**Low**	**High**	**High**
Engine Power, kW	212	145	145	115	115	115
Engine Configuration	V-8	V-8	V-8	V-6	V-6	V-6
Traction motor Power, kW peak	N/A	65.3	65.3	98	98	98
Battery Energy, kWh	N/A	5.19	5.19	9.3	9.3	11.0
Battery Module Costs, $/kWh	N/A	$255	$419	$337	$427	$455
Glider[a]	$27,022	$27,022	$27,022	$27,022	$27,022	$27,022
Engine + Exhaust	$7,490	$5,984	$5,984	$2,741	$2,741	$2,741
Transmission	$2,400	$1,600	$1,600	$1,600	$1,600	$1,600
Accessory Power	$488	$608	$608	$608	$608	$608
Electric Traction	$100	$2,770	$2,770	$3,838	$3,838	$3,838
Energy Storage System (ESS)	$60	$3,295	$4,146	$5,235	$6,072	$7,140
On Vehicle Charging System	—	—	—	$690	$690	$690
Total Price less Battery	$37,560	$41,279	$42,131	$43,441	$44,278	$45,345
Incremental Price	—	$3,719	$4,571	$5,881	$6,718	$7,785
Incremental Price less ESS	—	$485	$485	$706	$706	$706

[a] High cost of glider result of higher profit margin of SUVs as compared to mid-size cars.

Table A-8
SUV prices using ANL method at volume production

Vehicle Type	CV	HEV 0	PHEV 20	
Mileage Assumption	**Both**	**Both**	**Both**	**High**
Engine Power, kW	212	145	115	115
Engine Configuration	V-8	V-8	V-6	V-6
Traction motor Power, kW peak	N/A	65.3	98	98
Battery Energy, kWh	N/A	5.19	9.3	11.0
Battery Module Costs, $/kWh	N/A	$402	$352	$352
Glider[a]	$27,022	$27,022	$27,022	$27,022
Engine + Exhaust	$7,490	$5,984	$2,741	$2,741
Transmission	$2,400	$1,600	$1,600	$1,600
Accessory Power	$488	$608	$608	$608
Electric Traction	$100	$2,770	$3,838	$3,838
Energy Storage System (ESS)	$60	$4,058	$5,375	$6,007
On Vehicle Charging System	—	—	$690	$690
Total Price less Battery	$37,560	$42,042	$43,581	$44,212
Incremental Price	--	$4,482	$6,021	$6,652
Incremental Price less ESS	--	$485	$706	$706

[a] High cost of glider result of higher profit margin of SUVs as compared to mid-size cars.

Table A-9
Maintenance costs for Mid-Size CV

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	13,352	13,352	4	4	0	0	0	0	0	0	0	$200.28	$226.98	$586.26
2	12,948	26,300	4	4	1	0	0	0	0	0	0	$194.22	$220.12	$636.44
3	12,556	38,856	4	4	1	1	0	0	0	1	0	$188.34	$213.45	$904.89
4	12,176	51,032	5	5	1	0	0	0	0	0	0	$182.64	$206.99	$651.48
5	11,808	62,840	3	3	1	1	1	0	0	1	1	$177.12	$200.74	$1,145.31
6	11,450	74,290	4	4	0	0	0	0	0	0	0	$171.75	$194.65	$525.40
7	11,104	85,394	4	4	1	0	0	0	0	0	0	$166.56	$188.77	$577.43
8	10,768	96,162	4	4	1	1	0	0	0	1	0	$161.52	$183.06	$847.68
9	10,442	106,604	3	3	1	0	0	1	1	0	0	$156.63	$177.51	$884.03
10	10,126	116,730	3	3	0	0	0	0	0	0	0	$151.89	$172.14	$443.28
Total														$7,202.20

High Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	16,690	16,690	5	5	1	0	0	0	0	0	0	$250.35	$283.73	$795.93
2	16,273	32,963	5	5	1	1	0	0	0	1	0	$244.10	$276.64	$1,063.59
3	15,866	48,829	6	6	1	0	0	0	0	0	0	$237.99	$269.72	$809.31
4	15,469	64,298	5	5	1	1	1	0	0	1	1	$232.04	$262.97	$1,341.96
5	15,083	79,381	5	5	1	0	0	0	0	0	0	$226.25	$256.41	$744.51
6	14,705	94,086	5	5	1	1	0	0	0	1	0	$220.58	$249.99	$1,013.41
7	14,338	108,424	5	5	1	0	0	1	1	0	0	$215.07	$243.75	$1,088.21
8	13,979	122,403	4	4	1	1	1	0	0	1	1	$209.69	$237.64	$1,254.53
9	13,630	136,033	5	5	1	0	0	0	0	0	0	$204.45	$231.71	$698.01
10	13,289	149,322	4	4	0	0	0	0	0	0	0	$199.34	$225.91	$584.25
Total														$9,393.69

Table A-10
Maintenance costs for Mid-Size HEV 0

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	13,352	13,352	4	4	0	0	0	0	0	0	0	$200.28	$226.98	$568.86
2	12,948	26,300	4	4	1	0	0	0	0	0	0	$194.22	$220.12	$619.04
3	12,556	38,856	4	4	1	1	0	0	0	0	0	$188.34	$213.45	$632.49
4	12,176	51,032	5	5	1	0	0	0	0	0	0	$182.64	$206.99	$629.73
5	11,808	62,840	3	3	1	1	1	0	0	1	0	$177.12	$200.74	$868.56
6	11,450	74,290	4	4	0	0	0	0	0	0	0	$171.75	$194.65	$508.00
7	11,104	85,394	4	4	1	0	0	0	0	0	0	$166.56	$188.77	$560.03
8	10,768	96,162	4	4	1	1	0	0	0	0	0	$161.52	$183.06	$575.28
9	10,442	106,604	3	3	1	0	0	1	1	0	0	$156.63	$177.51	$870.98
10	10,126	116,730	3	3	0	0	0	0	0	0	0	$151.89	$172.14	$430.23
Total														$6,263.20

High Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	16,690	16,690	5	5	1	0	0	0	0	0	0	$250.35	$283.73	$774.18
2	16,273	32,963	5	5	1	1	0	0	0	0	0	$244.10	$276.64	$786.84
3	15,866	48,829	6	6	1	0	0	0	0	0	0	$237.99	$269.72	$783.21
4	15,469	64,298	5	5	1	1	1	0	0	1	0	$232.04	$262.97	$1,056.51
5	15,083	79,381	5	5	1	0	0	0	0	0	0	$226.25	$256.41	$722.76
6	14,705	94,086	5	5	1	1	0	0	0	0	0	$220.58	$249.99	$736.66
7	14,338	108,424	5	5	1	0	0	1	1	0	0	$215.07	$243.75	$1,066.46
8	13,979	122,403	4	4	1	1	1	0	0	1	1	$209.69	$237.64	$1,209.43
9	13,630	136,033	5	5	1	0	0	0	0	0	0	$204.45	$231.71	$676.26
10	13,289	149,322	4	4	0	0	0	0	0	0	0	$199.34	$225.91	$566.85
Total														$8,379.14

Table A-11
Maintenance costs for Mid-Size PHEV 20

Low Mileage Case

Years	Engine Miles	Vehicle Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	8,982	13,352	4	4	0	0	0	0	0	0	0	$200.28	$226.98	$568.86
2	17,692	26,300	4	4	1	0	0	0	0	0	0	$194.22	$220.12	$619.04
3	26,139	38,856	4	4	1	1	0	0	0	0	0	$188.34	$213.45	$632.49
4	34,330	51,032	5	5	1	0	0	0	0	0	0	$182.64	$206.99	$629.73
5	42,274	62,840	3	3	1	1	1	0	0	1	0	$177.12	$200.74	$868.56
6	49,976	74,290	4	4	0	0	0	0	0	0	0	$171.75	$194.65	$508.00
7	57,446	85,394	4	4	1	0	0	0	0	0	0	$166.56	$188.77	$560.03
8	64,690	96,162	4	4	1	1	0	0	0	0	0	$161.52	$183.06	$575.28
9	71,714	106,604	3	3	1	0	0	1	1	0	0	$156.63	$177.51	$870.98
10	78,526	116,730	3	3	0	0	0	0	0	0	0	$151.89	$172.14	$430.23
Total														$5,318.66

High Mileage Case

Years	Engine Miles	Vehicle Miles	Replacements									Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Belt	Front Pads	Front Rotors			
1	16,690	16,690	5	5	1	0	0	0	0	0	0	$250.35	$283.73	$774.18
2	16,273	32,963	5	5	1	1	0	0	0	0	0	$244.10	$276.64	$786.84
3	15,866	48,829	6	6	1	0	0	0	0	0	0	$237.99	$269.72	$783.21
4	15,469	64,298	5	5	1	1	1	0	0	1	0	$232.04	$262.97	$1,056.51
5	15,083	79,381	5	5	1	0	0	0	0	0	0	$226.25	$256.41	$722.76
6	14,705	94,086	5	5	1	1	0	0	0	0	0	$220.58	$249.99	$736.66
7	14,338	108,424	5	5	1	0	0	1	1	0	0	$215.07	$243.75	$1,066.46
8	13,979	122,403	4	4	1	1	1	0	0	1	1	$209.69	$237.64	$1,209.43
9	13,630	136,033	5	5	1	0	0	0	0	0	0	$204.45	$231.71	$676.26
10	13,289	149,322	4	4	0	0	0	0	0	0	0	$199.34	$225.91	$566.85
Total														$6,678.30

Table A-12
Maintenance costs for SUV CV

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	13,352	13,352	4	4	0	0	0	0	0	0	$200.28	$226.98	$599.26
2	12,948	26,300	4	4	0	0	0	0	0	0	$194.22	$220.12	$586.34
3	12,556	38,856	4	4	1	1	0	0	1	0	$188.34	$213.45	$917.60
4	12,176	51,032	5	5	0	0	0	0	0	0	$182.64	$206.99	$604.63
5	11,808	62,840	3	3	1	1	0	0	1	1	$177.12	$200.74	$1,214.67
6	11,450	74,290	4	4	0	0	0	0	0	0	$171.75	$194.65	$538.40
7	11,104	85,394	4	4	0	0	0	0	0	0	$166.56	$188.77	$527.33
8	10,768	96,162	4	4	1	1	0	1	1	0	$161.52	$183.06	$1,090.39
9	10,442	106,604	3	3	0	0	1	0	0	0	$156.63	$177.51	$610.94
10	10,126	116,730	3	3	0	0	0	0	0	0	$151.89	$172.14	$453.03
Total													$7,142.59

High Mileage Case

Years	Annual Miles	Total Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	16,690	16,690	5	5	0	0	0	0	0	0	$250.35	$283.73	$749.08
2	16,273	32,963	5	5	1	1	0	0	1	0	$244.10	$276.64	$1,079.55
3	15,866	48,829	6	6	0	0	0	0	0	0	$237.99	$269.72	$765.71
4	15,469	64,298	5	5	1	1	0	0	1	1	$232.04	$262.97	$1,417.82
5	15,083	79,381	5	5	0	0	0	0	0	0	$226.25	$256.41	$697.66
6	14,705	94,086	5	5	1	1	0	1	1	0	$220.58	$249.99	$1,259.37
7	14,338	108,424	5	5	0	0	1	0	0	0	$215.07	$243.75	$821.62
8	13,979	122,403	4	4	1	1	0	0	1	1	$209.69	$237.64	$1,327.14
9	13,630	136,033	5	5	0	0	0	0	0	0	$204.45	$231.71	$651.16
10	13,289	149,322	4	4	0	0	0	0	0	0	$199.34	$225.91	$597.25
Total													$9,366.34

Table A-13
Maintenance costs for SUV HEV 0

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	13,352	13,352	4	4	0	0	0	0	0	0	$200.28	$226.98	$599.26
2	12,948	26,300	4	4	0	0	0	0	0	0	$194.22	$220.12	$586.34
3	12,556	38,856	4	4	1	1	0	0	0	0	$188.34	$213.45	$637.60
4	12,176	51,032	5	5	0	0	0	0	0	0	$182.64	$206.99	$604.63
5	11,808	62,840	3	3	1	1	0	0	1	0	$177.12	$200.74	$850.67
6	11,450	74,290	4	4	0	0	0	0	0	0	$171.75	$194.65	$538.40
7	11,104	85,394	4	4	0	0	0	0	0	0	$166.56	$188.77	$527.33
8	10,768	96,162	4	4	1	1	0	1	0	0	$161.52	$183.06	$810.39
9	10,442	106,604	3	3	0	0	1	0	0	0	$156.63	$177.51	$610.94
10	10,126	116,730	3	3	0	0	0	0	0	0	$151.89	$172.14	$453.03
Total													$6,218.59

High Mileage Case

Years	Annual Miles	Total Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	16,690	16,690	5	5	0	0	0	0	0	0	$250.35	$283.73	$749.08
2	16,273	32,963	5	5	1	1	0	0	0	0	$244.10	$276.64	$799.55
3	15,866	48,829	6	6	0	0	0	0	0	0	$237.99	$269.72	$765.71
4	15,469	64,298	5	5	1	1	0	0	1	0	$232.04	$262.97	$1,053.82
5	15,083	79,381	5	5	0	0	0	0	0	0	$226.25	$256.41	$697.66
6	14,705	94,086	5	5	1	1	0	1	0	0	$220.58	$249.99	$979.37
7	14,338	108,424	5	5	0	0	1	0	0	0	$215.07	$243.75	$821.62
8	13,979	122,403	4	4	1	1	0	0	1	1	$209.69	$237.64	$1,327.14
9	13,630	136,033	5	5	0	0	0	0	0	0	$204.45	$231.71	$651.16
10	13,289	149,322	4	4	0	0	0	0	0	0	$199.34	$225.91	$597.25
Total													$8,442.34

Table A-14
Maintenance costs for SUV PHEV 20

Low Mileage Case

Years	Engine Miles	Vehicle Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	8,798	13,352	2	2	0	0	0	0	0	0	$200.28	$226.98	$504.56
2	17,330	26,300	3	3	0	0	0	0	0	0	$194.22	$220.12	$530.29
3	25,603	38,856	3	3	0	0	0	0	0	0	$188.34	$213.45	$517.74
4	33,627	51,032	3	3	1	1	0	0	0	0	$182.64	$206.99	$569.39
5	41,407	62,840	2	2	0	0	0	0	1	0	$177.12	$200.74	$735.16
6	48,952	74,290	3	3	1	0	0	0	0	0	$171.75	$194.65	$521.91
7	56,269	85,394	2	2	0	0	0	0	0	0	$166.56	$188.77	$432.63
8	63,364	96,162	3	3	1	1	1	0	0	0	$161.52	$183.06	$635.19
9	70,245	106,604	2	2	0	0	0	0	0	0	$156.63	$177.51	$411.44
10	76,917	116,730	2	2	1	0	0	0	0	0	$151.89	$172.14	$440.89
Total													$5,299.20

High Mileage Case

Years	Engine Miles	Vehicle Miles	Replacements								Other Maint Costs	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	Timing Belt	Front Pads	Front Rotors			
1	9,782	16,690	3	3	0	0	0	0	0	0	$250.35	$283.73	$650.03
2	19,319	32,963	3	3	0	0	0	0	0	0	$244.10	$276.64	$636.69
3	28,618	48,829	3	3	0	0	0	0	0	0	$237.99	$269.72	$623.66
4	37,684	64,298	3	3	1	1	0	0	1	0	$232.04	$262.97	$954.77
5	46,524	79,381	3	3	1	0	0	0	0	0	$226.25	$256.41	$638.17
6	55,142	94,086	3	3	0	0	0	0	0	0	$220.58	$249.99	$586.51
7	63,546	108,424	3	3	1	1	1	0	0	0	$215.07	$243.75	$749.43
8	71,739	122,403	2	2	0	0	0	0	1	1	$209.69	$237.64	$1,168.63
9	79,727	136,033	3	3	1	0	0	0	0	0	$204.45	$231.71	$591.67
10	87,516	149,322	3	3	0	0	0	0	0	0	$199.34	$225.91	$541.20
Total													$7,140.74

Table A-15
Net Present Value of Life Cycle Cost Calculation for Mid-size CV

Present Value Calculation—Based on ARB Vehicle 28

Gasoline Mid-size car

Discount rate:	8%
Gasoline, price per gallon	$1.75
ICE component cost:	$60
Miles per gallon	28.9
Inflation rate:	1.03

Low case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	13,352	$0	$1.750	$809	$586	$1,395
2	12,948	$0	$1.803	$808	$656	$1,463
3	12,556	$0	$1.857	$807	$960	$1,767
4	12,176	$0	$1.912	$806	$712	$1,518
5	11,808	$0	$1.970	$805	$1,289	$2,094
6	11,450	$0	$2.029	$804	$609	$1,413
7	11,104	$0	$2.090	$803	$689	$1,492
8	10,768	$0	$2.152	$802	$1,043	$1,844
9	10,442	$0	$2.217	$801	$1,120	$1,921
10	10,126	$0	$2.283	$800	$578	$1,378
Total	116,730	$60		$8,043	$8,242	$16,345
NPV of total		$60		$5,401	$5,445	$10,906
$ per mile		$0.001		$0.046	$0.047	$0.093

High case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	16,690	$0	$1.750	$1,011	$796	$1,807
2	16,273	$0	$1.803	$1,015	$1,095	$2,110
3	15,866	$0	$1.857	$1,019	$859	$1,878
4	15,469	$0	$1.912	$1,024	$1,466	$2,490
5	15,083	$0	$1.970	$1,028	$838	$1,866
6	14,705	$0	$2.029	$1,032	$1,175	$2,207
7	14,338	$0	$2.090	$1,037	$1,299	$2,336
8	13,979	$0	$2.152	$1,041	$1,543	$2,584
9	13,630	$0	$2.217	$1,046	$884	$1,930
10	13,289	$0	$2.283	$1,050	$762	$1,812
Total	149,322	$60		$10,302	$10,718	$21,080
NPV of total		$60		$6,894	$7,133	$14,088
$ per mile		$0.000		$0.046	$0.048	$0.094

Table A-16
Net Present Value of Life Cycle Cost Calculation for Mid-size HEV 0 (low mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$385
Pack capacity, kWh:	2.91
Energy Storage System Cost	$3,047
Incremental Vehicle Costs	-$547
Total Incremental Costs	$2,500
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	41.9
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$3,047	-$547				$2,500
1	13,352	13,352	$0	$0	$1.750	$557.66	$569	$1,127
2	12,948	12,948	$0	$0	$1.803	$557.01	$638	$1,195
3	12,556	12,556	$0	$0	$1.857	$556.35	$671	$1,227
4	12,176	12,176	$0	$0	$1.912	$555.70	$688	$1,244
5	11,808	11,808	$0	$0	$1.970	$555.07	$978	$1,533
6	11,450	11,450	$0	$0	$2.029	$554.39	$589	$1,143
7	11,104	11,104	$0	$0	$2.090	$553.77	$669	$1,222
8	10,768	10,768	$0	$0	$2.152	$553.12	$708	$1,261
9	10,442	10,442	$0	$0	$2.217	$552.47	$1,103	$1,656
10	10,126	10,126	-$116	$0	$2.283	$551.82	$561	$997
Total	116,730	116,730	$2,931	-$547		$5,547	$7,173	$15,104
NPV of total			$2,993	($547)		$3,725	$4,733	$10,903
$ per mile			$0.026	-$0.005		$0.032	$0.041	$0.093

Table A-17
Net Present Value of Life Cycle Cost Calculation for Mid-size HEV 0 (low mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$400
Pack capacity, kWh:	2.91
Energy Storage System Cost	$3,091
Incremental Vehicle Costs	-$547
Total Incremental Costs	$2,543
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	41.9
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$3,091	-$547				$2,543
1	13,352	13,352	$0	$0	$1.750	$557.66	$569	$1,127
2	12,948	12,948	$0	$0	$1.803	$557.01	$638	$1,195
3	12,556	12,556	$0	$0	$1.857	$556.35	$671	$1,227
4	12,176	12,176	$0	$0	$1.912	$555.70	$688	$1,244
5	11,808	11,808	$0	$0	$1.970	$555.07	$978	$1,533
6	11,450	11,450	$0	$0	$2.029	$554.39	$589	$1,143
7	11,104	11,104	$0	$0	$2.090	$553.77	$669	$1,222
8	10,768	10,768	$0	$0	$2.152	$553.12	$708	$1,261
9	10,442	10,442	$0	$0	$2.217	$552.47	$1,103	$1,656
10	10,126	10,126	-$116	$0	$2.283	$551.82	$561	$997
Total	116,730	116,730	$2,974	-$547		$5,547	$7,173	$15,147
NPV of total			$3,037	($547)		$3,725	$4,733	$10,947
$ per mile			$0.026	-$0.005		$0.032	$0.041	$0.094

Table A-18
Net Present Value of Life Cycle Cost Calculation for Mid-size HEV 0 (high mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$572
Pack capacity, kWh:	2.91
Energy Storage System Cost	$3,591
Incremental Vehicle Costs	-$547
Total Incremental Costs	$3,044
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	41.9
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$3,591	-$547				$3,044
1	16,690	16,690	$0	$0	$1.750	$697.08	$774	$1,473
2	16,273	16,273	$0	$0	$1.803	$700.05	$810	$1,512
3	15,866	15,866	$0	$0	$1.857	$703.02	$831	$1,536
4	15,469	15,469	$0	$0	$1.912	$705.99	$1,154	$1,862
5	15,083	15,083	$0	$0	$1.970	$709.02	$813	$1,524
6	14,705	14,705	$0	$0	$2.029	$711.99	$854	$1,568
7	14,338	14,338	$0	$0	$2.090	$715.05	$1,273	$1,991
8	13,979	13,979	$0	$0	$2.152	$718.06	$1,487	$2,208
9	13,630	13,630	$0	$0	$2.217	$721.14	$857	$1,580
10	13,289	13,289	-$116	$0	$2.283	$724.19	$740	$1,350
Total	149,322	149,322	$3,475	-$547		$7,106	$9,595	$19,648
NPV of total			$3,537	($547)		$4,755	$6,329	$14,088
$ per mile			$0.024	-$0.004		$0.032	$0.042	$0.094

Table A-19
Net Present Value of Life Cycle Cost Calculation for Mid-size HEV 0 (high mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$400
Pack capacity, kWh:	2.91
Energy Storage System Cost	$3,091
Incremental Vehicle Costs	-$547
Total Incremental Costs	$2,543
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	41.9
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$3,091	-$547				$2,543
1	16,690	16,690	$0	$0	$1.750	$697.08	$774	$1,473
2	16,273	16,273	$0	$0	$1.803	$700.05	$810	$1,512
3	15,866	15,866	$0	$0	$1.857	$703.02	$831	$1,536
4	15,469	15,469	$0	$0	$1.912	$705.99	$1,154	$1,862
5	15,083	15,083	$0	$0	$1.970	$709.02	$813	$1,524
6	14,705	14,705	$0	$0	$2.029	$711.99	$854	$1,568
7	14,338	14,338	$0	$0	$2.090	$715.05	$1,273	$1,991
8	13,979	13,979	$0	$0	$2.152	$718.06	$1,487	$2,208
9	13,630	13,630	$0	$0	$2.217	$721.14	$857	$1,580
10	13,289	13,289	-$116	$0	$2.283	$724.19	$740	$1,350
Total	149,322	149,322	$2,974	-$547		$7,106	$9,595	$19,147
NPV of total			$3,037	($547)		$4,755	$6,329	$13,587
$ per mile			$0.020	-$0.004		$0.032	$0.042	$0.091

Table A-20
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (low mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$316
Pack capacity, kWh	5.88
Cycle life	2,000
Energy Storage System Costs	$3,893
Incremental Vehicle Costs	$224
Total Incremental Costs	$4,117
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$3,893	$224							$4,117
1	13,352	4,370	8,982	$0	$0	$0.050	$1.750	$361	$62	$424	$498	$922
2	12,948	4,238	8,710	$0	$0	$0.052	$1.803	$361	$60	$421	$601	$1,023
3	12,556	4,109	8,447	$0	$0	$0.053	$1.857	$361	$59	$419	$539	$958
4	12,176	3,985	8,191	$0	$0	$0.055	$1.912	$360	$57	$417	$639	$1,056
5	11,808	3,865	7,943	$0	$0	$0.056	$1.970	$360	$55	$415	$826	$1,241
6	11,450	3,747	7,703	$0	$0	$0.058	$2.029	$359	$53	$413	$580	$993
7	11,104	3,634	7,470	$0	$0	$0.060	$2.090	$359	$52	$411	$551	$962
8	10,768	3,524	7,244	$0	$0	$0.061	$2.152	$358	$50	$409	$676	$1,085
9	10,442	3,417	7,025	$0	$0	$0.063	$2.217	$358	$49	$407	$513	$920
10	10,126	3,314	6,812	-$93	$0	$0.065	$2.283	$358	$47	$405	$644	$956
Total	116,730	38,204	78,526	$3,800	$224			$3,595	$545	$4,140	$6,068	$14,231
NPV of total				$3,850	$224			$2,414	$373	$2,787	$4,044	$10,904
$ per mile				$0.033	$0.002			$0.021	$0.003	$0.024	$0.051	$0.093

Table A-21
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (low mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$320
Pack capacity, kWh	5.88
Cycle life	2,000
Energy Storage System Costs	$3,916
Incremental Vehicle Costs	$224
Total Incremental Costs	$4,141
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	**Total Mileage**	**Elect Miles**	**Gas Miles**	**Pack Cost**	**Delta Vehicle Price**	**Elect Price**	**Gas Price**	**Gas Fuel**	**Elect Fuel**	**Total Fuel**	**Maintenance**	**Total**
0	0			$3,916	$224							$4,141
1	13,352	4,370	8,982	$0	$0	$0.050	$1.750	$361	$62	$424	$498	$922
2	12,948	4,238	8,710	$0	$0	$0.052	$1.803	$361	$60	$421	$601	$1,023
3	12,556	4,109	8,447	$0	$0	$0.053	$1.857	$361	$59	$419	$539	$958
4	12,176	3,985	8,191	$0	$0	$0.055	$1.912	$360	$57	$417	$639	$1,056
5	11,808	3,865	7,943	$0	$0	$0.056	$1.970	$360	$55	$415	$826	$1,241
6	11,450	3,747	7,703	$0	$0	$0.058	$2.029	$359	$53	$413	$580	$993
7	11,104	3,634	7,470	$0	$0	$0.060	$2.090	$359	$52	$411	$551	$962
8	10,768	3,524	7,244	$0	$0	$0.061	$2.152	$358	$50	$409	$676	$1,085
9	10,442	3,417	7,025	$0	$0	$0.063	$2.217	$358	$49	$407	$513	$920
10	10,126	3,314	6,812	-$94	$0	$0.065	$2.283	$358	$47	$405	$644	$954
Total	116,730	38,204	78,526	$3,822	$224			$3,595	$545	$4,140	$6,068	$14,254
NPV of total				$3,873	$224			$2,414	$373	$2,787	$4,044	$10,927
$ per mile				$0.033	$0.002			$0.021	$0.003	$0.024	$0.051	$0.094

Table A-22
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (high mileage cost parity small battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$380
Pack capacity, kWh	5.88
Cycle life	2,000
Energy Storage System Costs	$4,269
Incremental Vehicle Costs	$224
Total Incremental Costs	$4,493
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$4,269	$224							$4,493
1	16,690	4,370	12,320	$0	$0	$0.050	$1.750	$496	$62	$558	$676	$1,234
2	16,273	4,238	12,035	$0	$0	$0.052	$1.803	$499	$62	$561	$747	$1,308
3	15,866	4,109	11,757	$0	$0	$0.053	$1.857	$502	$62	$564	$783	$1,347
4	15,469	3,985	11,484	$0	$0	$0.055	$1.912	$505	$62	$567	$999	$1,566
5	15,083	3,865	11,218	$0	$0	$0.056	$1.970	$508	$62	$570	$703	$1,273
6	14,705	3,747	10,958	$0	$0	$0.058	$2.029	$511	$62	$573	$866	$1,439
7	14,338	3,634	10,704	$0	$0	$0.060	$2.090	$514	$62	$576	$750	$1,326
8	13,979	3,524	10,455	$0	$0	$0.061	$2.152	$517	$62	$579	$1,432	$2,011
9	13,630	3,417	10,213	$0	$0	$0.063	$2.217	$520	$62	$582	$1,153	$1,735
10	13,289	3,314	9,975	-$94	$0	$0.065	$2.283	$524	$62	$585	$822	$1,313
Total	149,322	38,204	111,118	$4,175	$224			$5,095	$620	$5,716	$8,930	$19,045
NPV of total				$4,225	$224			$2,189	$848	$3,406	$416	$3,822
$ per mile				$0.028	$0.002			$0.015	$0.006	$0.023	$0.003	$0.026

Table A-23
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (high mileage volume production small battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$320
Pack capacity, kWh	5.88
Cycle life	2,000
Energy Storage System Costs	$3,916
Incremental Vehicle Costs	$224
Total Incremental Costs	$4,141
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$3,916	$224							$4,141
1	16,690	4,370	12,320	$0	$0	$0.050	$1.750	$496	$62	$558	$676	$1,234
2	16,273	4,238	12,035	$0	$0	$0.052	$1.803	$499	$62	$561	$747	$1,308
3	15,866	4,109	11,757	$0	$0	$0.053	$1.857	$502	$62	$564	$783	$1,347
4	15,469	3,985	11,484	$0	$0	$0.055	$1.912	$505	$62	$567	$999	$1,566
5	15,083	3,865	11,218	$0	$0	$0.056	$1.970	$508	$62	$570	$703	$1,273
6	14,705	3,747	10,958	$0	$0	$0.058	$2.029	$511	$62	$573	$866	$1,439
7	14,338	3,634	10,704	$0	$0	$0.060	$2.090	$514	$62	$576	$750	$1,326
8	13,979	3,524	10,455	$0	$0	$0.061	$2.152	$517	$62	$579	$1,432	$2,011
9	13,630	3,417	10,213	$0	$0	$0.063	$2.217	$520	$62	$582	$1,153	$1,735
10	13,289	3,314	9,975	-$94	$0	$0.065	$2.283	$524	$62	$585	$822	$1,313
Total	149,322	38,204	111,118	$3,822	$224			$5,095	$620	$5,716	$8,930	$18,692
NPV of total				$3,873	$224			$2,189	$848	$3,406	$416	$13,734
$ per mile				$0.026	$0.002			$0.015	$0.006	$0.020	$0.071	$0.092

Table A-24
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (high mileage cost parity large battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$471
Pack capacity, kWh	8.00
Cycle life	4,000
Energy Storage System Costs	$5,844
Incremental Vehicle Costs	$224
Total Incremental Costs	$6,068
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$5,844	$224							$6,068
1	16,690	8,714	7,976	$0	$0	$0.050	$1.750	$320.85	$124	$445	$605	$1,050
2	16,273	8,497	7,776	$0	$0	$0.052	$1.803	$322.22	$125	$447	$711	$1,158
3	15,866	8,284	7,582	$0	$0	$0.053	$1.857	$323.59	$125	$449	$614	$1,063
4	15,469	8,077	7,392	$0	$0	$0.055	$1.912	$324.96	$126	$451	$1,027	$1,478
5	15,083	7,875	7,208	$0	$0	$0.056	$1.970	$326.35	$126	$453	$623	$1,076
6	14,705	7,678	7,027	$0	$0	$0.058	$2.029	$327.72	$127	$455	$628	$1,082
7	14,338	7,486	6,852	$0	$0	$0.060	$2.090	$329.13	$128	$457	$750	$1,207
8	13,979	7,299	6,680	$0	$0	$0.061	$2.152	$330.51	$128	$459	$1,235	$1,694
9	13,630	7,117	6,513	$0	$0	$0.063	$2.217	$331.93	$129	$461	$813	$1,273
10	13,289	6,939	6,350	-$128	$0	$0.065	$2.283	$333.33	$129	$462	$647	$982
Total	149,322	77,967	71,355	$5,716	$224			$3,271	$1,267	$4,538	$7,652	$18,130
NPV of total				$5,785	$224			$2,189	$848	$3,037	$5,042	$14,088
$ per mile				$0.039	$0.002			$0.015	$0.006	$0.020	$0.071	$0.095

Table A-25
Net Present Value of Life Cycle Cost Calculation for Mid-size PHEV 20 (high mileage volume production large battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$320
Pack capacity, kWh	8.00
Cycle life	4,000
Energy Storage System Costs	$4,636
Incremental Vehicle Costs	$224
Total Incremental Costs	$4,860
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	43.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.2853
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$4,636	$224							$4,860
1	16,690	8,714	7,976	$0	$0	$0.050	$1.750	$320.85	$124	$445	$605	$1,050
2	16,273	8,497	7,776	$0	$0	$0.052	$1.803	$322.22	$125	$447	$711	$1,158
3	15,866	8,284	7,582	$0	$0	$0.053	$1.857	$323.59	$125	$449	$614	$1,063
4	15,469	8,077	7,392	$0	$0	$0.055	$1.912	$324.96	$126	$451	$1,027	$1,478
5	15,083	7,875	7,208	$0	$0	$0.056	$1.970	$326.35	$126	$453	$623	$1,076
6	14,705	7,678	7,027	$0	$0	$0.058	$2.029	$327.72	$127	$455	$628	$1,082
7	14,338	7,486	6,852	$0	$0	$0.060	$2.090	$329.13	$128	$457	$750	$1,207
8	13,979	7,299	6,680	$0	$0	$0.061	$2.152	$330.51	$128	$459	$1,235	$1,694
9	13,630	7,117	6,513	$0	$0	$0.063	$2.217	$331.93	$129	$461	$813	$1,273
10	13,289	6,939	6,350	-$128	$0	$0.065	$2.283	$333.33	$129	$462	$647	$982
Total	149,322	77,967	71,355	$4,508	$224			$3,271	$1,267	$4,538	$7,652	$16,922
NPV of total				$4,577	$224			$2,189	$848	$3,037	$5,042	$12,880
$ per mile				$0.031	$0.002			$0.015	$0.006	$0.020	$0.071	$0.086

Table A-26
Net Present Value of Life Cycle Cost Calculation for SUV CV

Present Value Calculation—Based on ARB Vehicle 28.1
Gasoline SUV

Discount rate:	8%
Gasoline, price per gallon	$1.75
ICE component cost:	$60
Miles per gallon	28.9
Inflation rate:	1.03

Low case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	13,352	$0	$1.750	$1,284	$599	$1,883
2	12,948	$0	$1.803	$1,282	$604	$1,886
3	12,556	$0	$1.857	$1,281	$973	$2,254
4	12,176	$0	$1.912	$1,279	$661	$1,940
5	11,808	$0	$1.970	$1,278	$1,367	$2,645
6	11,450	$0	$2.029	$1,276	$624	$1,900
7	11,104	$0	$2.090	$1,275	$630	$1,905
8	10,768	$0	$2.152	$1,273	$1,341	$2,614
9	10,442	$0	$2.217	$1,272	$774	$2,046
10	10,126	$0	$2.283	$1,270	$591	$1,862
Total	116,730	$60		$12,771	$8,164	$20,995
NPV of total		$60		$8,576	$5,408	$14,044
$ per mile		$0.001		$0.073	$0.046	$0.120

High case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	16,690	$0	$1.750	$1,605	$749	$2,354
2	16,273	$0	$1.803	$1,612	$1,112	$2,724
3	15,866	$0	$1.857	$1,618	$812	$2,431
4	15,469	$0	$1.912	$1,625	$1,549	$3,175
5	15,083	$0	$1.970	$1,632	$785	$2,418
6	14,705	$0	$2.029	$1,639	$1,460	$3,099
7	14,338	$0	$2.090	$1,646	$981	$2,627
8	13,979	$0	$2.152	$1,653	$1,632	$3,285
9	13,630	$0	$2.217	$1,660	$825	$2,485
10	13,289	$0	$2.283	$1,667	$779	$2,446
Total	149,322	$60		$16,358	$10,685	$27,104
NPV of total		$60		$10,947	$7,113	$18,120
$ per mile		$0.000		$0.073	$0.048	$0.121

Table A-27
Net Present Value of Life Cycle Cost Calculation for SUV HEV 0 (low mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$255
Pack capacity, kWh:	5.19
Energy Storage System Cost	$3,295
Incremental Vehicle Costs	$485
Total Incremental Costs	$3,779
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	27.6
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$3,295	$485				$3,779
1	13,352	13,352	$0	$0	$1.750	$846.59	$599	$1,446
2	12,948	12,948	$0	$0	$1.803	$845.61	$604	$1,450
3	12,556	12,556	$0	$0	$1.857	$844.61	$676	$1,521
4	12,176	12,176	$0	$0	$1.912	$843.62	$661	$1,504
5	11,808	11,808	$0	$0	$1.970	$842.66	$957	$1,800
6	11,450	11,450	$0	$0	$2.029	$841.63	$624	$1,466
7	11,104	11,104	$0	$0	$2.090	$840.68	$630	$1,470
8	10,768	10,768	$0	$0	$2.152	$839.70	$997	$1,836
9	10,442	10,442	$0	$0	$2.217	$838.71	$774	$1,613
10	10,126	10,126	-$208	$0	$2.283	$837.73	$591	$1,221
Total	116,730	116,730	$3,087	$485		$8,422	$7,113	$19,107
NPV of total			$3,198	$485		$5,655	$4,707	$14,045
$ per mile			$0.027	$0.004		$0.048	$0.040	$0.120

Table A-28
Net Present Value of Life Cycle Cost Calculation for SUV HEV 0 (low mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$402
Pack capacity, kWh:	5.19
Energy Storage System Cost	$4,058
Incremental Vehicle Costs	$485
Total Incremental Costs	$4,542
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	27.6
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$4,058	$485				$4,542
1	13,352	13,352	$0	$0	$1.750	$846.59	$599	$1,446
2	12,948	12,948	$0	$0	$1.803	$845.61	$604	$1,450
3	12,556	12,556	$0	$0	$1.857	$844.61	$676	$1,521
4	12,176	12,176	$0	$0	$1.912	$843.62	$661	$1,504
5	11,808	11,808	$0	$0	$1.970	$842.66	$957	$1,800
6	11,450	11,450	$0	$0	$2.029	$841.63	$624	$1,466
7	11,104	11,104	$0	$0	$2.090	$840.68	$630	$1,470
8	10,768	10,768	$0	$0	$2.152	$839.70	$997	$1,836
9	10,442	10,442	$0	$0	$2.217	$838.71	$774	$1,613
10	10,126	10,126	-$208	$0	$2.283	$837.73	$591	$1,221
Total	116,730	116,730	$3,850	$485		$8,422	$7,113	$19,870
NPV of total			$3,961	$485		$5,655	$4,707	$14,808
$ per mile			$0.034	$0.004		$0.048	$0.040	$0.127

Table A-29
Net Present Value of Life Cycle Cost Calculation for SUV HEV 0 (high mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$419
Pack capacity, kWh:	5.19
Energy Storage System Cost	$4,146
Incremental Vehicle Costs	$485
Total Incremental Costs	$4,631
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	27.6
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$4,146	$485				$4,631
1	16,690	16,690	$0	$0	$1.750	$1,058.24	$749	$1,807
2	16,273	16,273	$0	$0	$1.803	$1,062.76	$824	$1,886
3	15,866	15,866	$0	$0	$1.857	$1,067.26	$812	$1,880
4	15,469	15,469	$0	$0	$1.912	$1,071.77	$1,152	$2,223
5	15,083	15,083	$0	$0	$1.970	$1,076.38	$785	$1,862
6	14,705	14,705	$0	$0	$2.029	$1,080.89	$1,135	$2,216
7	14,338	14,338	$0	$0	$2.090	$1,085.53	$981	$2,067
8	13,979	13,979	$0	$0	$2.152	$1,090.10	$1,632	$2,722
9	13,630	13,630	$0	$0	$2.217	$1,094.77	$825	$1,920
10	13,289	13,289	-$208	$0	$2.283	$1,099.40	$779	$1,671
Total	149,322	149,322	$3,938	$485		$10,787	$9,674	$24,885
NPV of total			$4,050	$485		$7,219	$6,369	$18,122
$ per mile			$0.027	$0.003		$0.048	$0.043	$0.121

Table A-30
Net Present Value of Life Cycle Cost Calculation for SUV HEV 0 (high mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$402
Pack capacity, kWh:	5.19
Energy Storage System Cost	$4,058
Incremental Vehicle Costs	$485
Total Incremental Costs	$4,542
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$40
Miles per gallon	27.6
Gasoline Price per gallon	$1.75
Inflation rate:	1.03

Year	Mileage	Gasoline miles	Pack Cost	Vehicle Costs	Gasoline Price	Total Gasoline	Gasoline maintenance	Total
0	0		$4,058	$485				$4,542
1	16,690	16,690	$0	$0	$1.750	$1,058.24	$749	$1,807
2	16,273	16,273	$0	$0	$1.803	$1,062.76	$824	$1,886
3	15,866	15,866	$0	$0	$1.857	$1,067.26	$812	$1,880
4	15,469	15,469	$0	$0	$1.912	$1,071.77	$1,152	$2,223
5	15,083	15,083	$0	$0	$1.970	$1,076.38	$785	$1,862
6	14,705	14,705	$0	$0	$2.029	$1,080.89	$1,135	$2,216
7	14,338	14,338	$0	$0	$2.090	$1,085.53	$981	$2,067
8	13,979	13,979	$0	$0	$2.152	$1,090.10	$1,632	$2,722
9	13,630	13,630	$0	$0	$2.217	$1,094.77	$825	$1,920
10	13,289	13,289	-$208	$0	$2.283	$1,099.40	$779	$1,671
Total	149,322	149,322	$3,850	$485		$10,787	$9,674	$24,796
NPV of total			$3,961	$485		$7,219	$6,369	$18,034
$ per mile			$0.027	$0.003		$0.048	$0.043	$0.121

Table A-31
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (low mileage cost parity case)

Discount rate:	8%
Battery cost, $ per kWh:	$337
Pack capacity, kWh	9.3
Cycle Life	2,000
Energy Storage System Costs	$5,235
Incremental Vehicle Costs	$706
Total Incremental Costs	$5,941
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$5,235	$706							$5,941
1	13,352	4,554	8,798	$0	$0	$0.050	$1.750	$521.92	$99	$621	$505	$1,125
2	12,948	4,416	8,532	$0	$0	$0.052	$1.803	$521.31	$98	$620	$546	$1,166
3	12,556	4,282	8,274	$0	$0	$0.053	$1.857	$520.69	$98	$619	$549	$1,168
4	12,176	4,153	8,023	$0	$0	$0.055	$1.912	$520.08	$98	$618	$622	$1,241
5	11,808	4,027	7,781	$0	$0	$0.056	$1.970	$519.49	$98	$618	$827	$1,445
6	11,450	3,905	7,545	$0	$0	$0.058	$2.029	$518.86	$98	$617	$605	$1,222
7	11,104	3,787	7,317	$0	$0	$0.060	$2.090	$518.27	$98	$616	$517	$1,133
8	10,768	3,673	7,095	$0	$0	$0.061	$2.152	$517.67	$98	$615	$781	$1,397
9	10,442	3,561	6,881	$0	$0	$0.063	$2.217	$517.06	$98	$615	$521	$1,136
10	10,126	3,454	6,672	-$149	$0	$0.065	$2.283	$516.45	$98	$614	$575	$1,040
Total	116,730	39,813	76,917	$5,087	$706			$5,192	$981	$6,173	$6,094	$18,014
NPV of total				$5,167	$706			$3,486	$659	$4,145	$4,024	$14,041
$ per mile				$0.044	$0.006			$0.030	$0.006	$0.036	$0.034	$0.120

Table A-32
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (low mileage volume production case)

Discount rate:	8%
Battery cost, $ per kWh:	$352
Pack capacity, kWh	9.3
Cycle Life	2,000
Energy Storage System Costs	$5,375
Incremental Vehicle Costs	$706
Total Incremental Costs	$6,081
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh	$16
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$5,375	$706							$6,081
1	13,352	4,554	8,798	$0	$0	$0.050	$1.750	$521.92	$99	$621	$505	$1,125
2	12,948	4,416	8,532	$0	$0	$0.052	$1.803	$521.31	$98	$620	$546	$1,166
3	12,556	4,282	8,274	$0	$0	$0.053	$1.857	$520.69	$98	$619	$549	$1,168
4	12,176	4,153	8,023	$0	$0	$0.055	$1.912	$520.08	$98	$618	$622	$1,241
5	11,808	4,027	7,781	$0	$0	$0.056	$1.970	$519.49	$98	$618	$827	$1,445
6	11,450	3,905	7,545	$0	$0	$0.058	$2.029	$518.86	$98	$617	$605	$1,222
7	11,104	3,787	7,317	$0	$0	$0.060	$2.090	$518.27	$98	$616	$517	$1,133
8	10,768	3,673	7,095	$0	$0	$0.061	$2.152	$517.67	$98	$615	$781	$1,397
9	10,442	3,561	6,881	$0	$0	$0.063	$2.217	$517.06	$98	$615	$521	$1,136
10	10,126	3,454	6,672	-$149	$0	$0.065	$2.283	$516.45	$98	$614	$575	$1,040
Total	116,730	39,813	76,917	$5,226	$706			$5,192	$981	$6,173	$6,094	$18,153
NPV of total				$5,306	$706			$3,486	$659	$4,145	$4,024	$14,180
$ per mile				$0.045	$0.006			$0.030	$0.006	$0.036	$0.034	$0.121

Table A-33
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (high mileage cost parity small battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$427
Pack capacity, kWh	9.3
Cycle Life	2,000
Energy Storage System Costs	$6,072
Incremental Vehicle Costs	$706
Total Incremental Costs	$6,778
Pack life, years:	10
Pack salvage value, $ per kWh	$16
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$6,072	$706							$6,778
1	16,690	4,554	12,136	$0	$0	$0.050	$1.750	$720	$99	$819	$689	$1,507
2	16,273	4,416	11,857	$0	$0	$0.052	$1.803	$724	$98	$823	$656	$1,479
3	15,866	4,282	11,584	$0	$0	$0.053	$1.857	$729	$98	$827	$770	$1,598
4	15,469	4,153	11,316	$0	$0	$0.055	$1.912	$734	$98	$832	$1,059	$1,891
5	15,083	4,027	11,056	$0	$0	$0.056	$1.970	$738	$98	$836	$717	$1,554
6	14,705	3,905	10,800	$0	$0	$0.058	$2.029	$743	$98	$841	$882	$1,723
7	14,338	3,787	10,551	$0	$0	$0.060	$2.090	$747	$98	$845	$780	$1,625
8	13,979	3,673	10,306	$0	$0	$0.061	$2.152	$752	$98	$850	$1,485	$2,335
9	13,630	3,561	10,069	$0	$0	$0.063	$2.217	$757	$98	$854	$1,121	$1,975
10	13,289	3,454	9,835	-$149	$0	$0.065	$2.283	$761	$98	$859	$758	$1,468
Total	149,322	39,813	109,509	$5,924	$706			$7,405	$981	$8,386	$8,916	$23,931
		NPV of total		$6,004	$706			$4,949	$659	$5,608	$5,803	$18,120
		$ per mile		$0.040	$0.005			$0.033	$0.004	$0.038	$0.039	$0.121

Table A-34
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (high mileage vol. production small battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$352
Pack capacity, kWh	9.3
Cycle Life	2,000
Energy Storage System Costs	$5,375
Incremental Vehicle Costs	$706
Total Incremental Costs	$6,081
Pack life, years:	10
Pack salvage value, $ per kWh	$15
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$5,375	$706							$6,081
1	16,690	4,554	12,136	$0	$0	$0.050	$1.750	$720	$99	$819	$689	$1,507
2	16,273	4,416	11,857	$0	$0	$0.052	$1.803	$724	$98	$823	$656	$1,479
3	15,866	4,282	11,584	$0	$0	$0.053	$1.857	$729	$98	$827	$770	$1,598
4	15,469	4,153	11,316	$0	$0	$0.055	$1.912	$734	$98	$832	$1,059	$1,891
5	15,083	4,027	11,056	$0	$0	$0.056	$1.970	$738	$98	$836	$717	$1,554
6	14,705	3,905	10,800	$0	$0	$0.058	$2.029	$743	$98	$841	$882	$1,723
7	14,338	3,787	10,551	$0	$0	$0.060	$2.090	$747	$98	$845	$780	$1,625
8	13,979	3,673	10,306	$0	$0	$0.061	$2.152	$752	$98	$850	$1,485	$2,335
9	13,630	3,561	10,069	$0	$0	$0.063	$2.217	$757	$98	$854	$1,121	$1,975
10	13,289	3,454	9,835	-$149	$0	$0.065	$2.283	$761	$98	$859	$758	$1,468
Total	149,322	39,813	109,509	$5,226	$706			$7,405	$981	$8,386	$8,916	$23,234
NPV of total				$5,306	$706			$4,949	$659	$5,608	$5,803	$17,422
$ per mile				$0.036	$0.005			$0.033	$0.004	$0.038	$0.039	$0.117

Table A-35
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (high mileage cost parity large battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$455
Pack capacity, kWh	11.0
Cycle Life	3,000
Energy Storage System Costs	$7,140
Incremental Vehicle Costs	$706
Total Incremental Costs	$7,845
Pack life, years:	10
Pack salvage value, $ per kWh	$16
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$7,140	$706							$7,845
1	16,690	6,908	9,782	$0	$0	$0.050	$1.750	$580.27	$150	$730	$650	$1,380
2	16,273	6,736	9,537	$0	$0	$0.052	$1.803	$582.75	$150	$733	$656	$1,389
3	15,866	6,567	9,299	$0	$0	$0.053	$1.857	$585.22	$151	$736	$662	$1,398
4	15,469	6,403	9,066	$0	$0	$0.055	$1.912	$587.69	$151	$739	$1,043	$1,782
5	15,083	6,243	8,840	$0	$0	$0.056	$1.970	$590.22	$152	$742	$718	$1,461
6	14,705	6,087	8,618	$0	$0	$0.058	$2.029	$592.69	$153	$745	$680	$1,425
7	14,338	5,935	8,403	$0	$0	$0.060	$2.090	$595.24	$153	$749	$895	$1,644
8	13,979	5,786	8,193	$0	$0	$0.061	$2.152	$597.74	$154	$752	$1,437	$2,189
9	13,630	5,642	7,988	$0	$0	$0.063	$2.217	$600.30	$155	$755	$750	$1,505
10	13,289	5,501	7,788	-$176	$0	$0.065	$2.283	$602.84	$155	$758	$706	$1,288
Total	149,322	61,806	87,516	$6,964	$706			$5,915	$1,525	$7,440	$8,197	$23,305
NPV of total				$7,058	$706			$3,958	$1,020	$4,979	$5,374	$18,116
$ per mile				$0.047	$0.005			$0.027	$0.007	$0.033	$0.036	$0.121

Table A-36
Net Present Value of Life Cycle Cost Calculation for SUV PHEV 20 (high mileage volume production large battery case)

Discount rate:	8%
Battery cost, $ per kWh:	$352
Pack capacity, kWh	11.0
Cycle Life	3,000
Energy Storage System Costs	$6,007
Incremental Vehicle Costs	$706
Total Incremental Costs	$6,712
Pack life, years:	10
Pack salvage value, $ per kWh	$16
Miles per gallon	29.5
Gasoline Price per gallon	$1.75
Electricity cost, $ per kWh:	$0.05
kWh per mile:	0.433
Charger Efficiency	82%
Inflation rate:	1.03

Year	Total Mileage	Elect Miles	Gas Miles	Pack Cost	Delta Vehicle Price	Elect Price	Gas Price	Gas Fuel	Elect Fuel	Total Fuel	Maintenance	Total
0	0			$6,007	$706							$6,712
1	16,690	6,908	9,782	$0	$0	$0.050	$1.750	$580.27	$150	$730	$650	$1,380
2	16,273	6,736	9,537	$0	$0	$0.052	$1.803	$582.75	$150	$733	$656	$1,389
3	15,866	6,567	9,299	$0	$0	$0.053	$1.857	$585.22	$151	$736	$662	$1,398
4	15,469	6,403	9,066	$0	$0	$0.055	$1.912	$587.69	$151	$739	$1,043	$1,782
5	15,083	6,243	8,840	$0	$0	$0.056	$1.970	$590.22	$152	$742	$718	$1,461
6	14,705	6,087	8,618	$0	$0	$0.058	$2.029	$592.69	$153	$745	$680	$1,425
7	14,338	5,935	8,403	$0	$0	$0.060	$2.090	$595.24	$153	$749	$895	$1,644
8	13,979	5,786	8,193	$0	$0	$0.061	$2.152	$597.74	$154	$752	$1,437	$2,189
9	13,630	5,642	7,988	$0	$0	$0.063	$2.217	$600.30	$155	$755	$750	$1,505
10	13,289	5,501	7,788	-$176	$0	$0.065	$2.283	$602.84	$155	$758	$706	$1,288
Total	149,322	61,806	87,516	$5,831	$706			$5,915	$1,525	$7,440	$8,197	$22,172
NPV of total				$5,925	$706			$3,958	$1,020	$4,979	$5,374	$16,983
$ per mile				$0.040	$0.005			$0.027	$0.007	$0.033	$0.036	$0.114

B

CITY BEV LIFE CYCLE COSTS

Table B-1 gives the maximum cost to manufacturer allowable for BEVs to reach life cycle cost parity with the CV for City Cars. These costs are assumed to occur in early production levels.

Table B-2 gives the maximum vehicle price to consumers for BEV 40s to have life cycle cost parity with the CV for city cars. This uses the ANL method to calculate a cost based price.

Maintenance costs are shown in Table B-3 for the city car CV, Table B-4 for the city BEV 40.

Net present value of life cycle cost calculations are shown in Table B-5 through Table B-7.

Table B-1
City Car costs to manufacturer

Vehicle Type	**CV**	**BEV 40**	
Mileage Assumption	**Both**	**Low**	**High**
Engine Power, kW	36		
Engine Configuration	I-3		
Traction motor Power, kW peak	N/A	27	27
Battery Energy, kWh	N/A	9.00	9.5
Battery Module Costs, $/kWh	N/A	257	364
Engine	856		
Engine Thermal	8		
Engine Total	**864**		
Exhaust System	**150**		
Transmission	**800**	**500**	**500**
Power Steering Pump	45	45	45
Generator/Alternator	35		
A/C Compressor	80	80	80
A/C Condenser	16	16	16
APM	0	120	120
Accessory Power Total	**176**	**261**	**261**
Starter Motor	30		
Electric Motor		560	560
Power Inverter		356	356
Electronics Thermal		97	97
Electric Traction Total	**30**	**1013**	**1013**
Fuel Storage (tank)	10		
Accessory Battery	20	15	15
Energy Batteries		2313	3458
Pack Tray		175	178
Pack Hardware		505	523
Battery Thermal		117	128
Energy Storage Total	**30**	**3125**	**4277**
Charger		380	380
Cable		80	80
Charging Total	**0**	**460**	**460**
Total	**2050**	**5359**	**6510**
Incremental		3258	4410

Table B-2
City Car using ANL method

Vehicle Type	**CV**	**HEV 0**	
Mileage Assumption	**Both**	**Low**	**High**
Engine Power, kW	36		
Engine Configuration	I-3		
Traction motor Power, kW peak	N/A	27	27
Battery Energy, kWh	N/A	9	9.5
Battery Module Costs, $/kWh	N/A	$236	$360
Glider	$7,799	$7,799	$7,799
Engine + Exhaust	$2,129	$0	$0
Transmission	$1,600	$1,000	$1,000
Accessory Power	$352	$462	$462
Electric Traction	$60	$1,519	$1,519
Energy Storage System (ESS)	$60	$4,389	$5,543
On Vehicle Charging System	--	$690	$690
Total Price	$12,000	$15,859	$18,164
Incremental Price	--	$3,859	$6,164
Incremental Price less ESS	--	($470)	($470)

Table B-3
Maintenance costs for City Car CV

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Engine Maintenance	Non-engine Maint	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Chain	Front Pads	Front Rotors				
1	10,014	10,014	2	2	0	0	0	0	0	0	0	$20.03	$140.20	$170.24	$403.68
2	9,711	19,725	1	1	1	0	0	0	0	0	0	$39.45	$135.95	$165.09	$412.60
3	9,417	29,142	2	2	0	0	0	0	0	0	0	$58.28	$131.84	$160.09	$423.43
4	9,132	38,274	2	2	1	1	0	0	0	1	0	$76.55	$127.85	$155.24	$700.24
5	8,856	47,130	2	2	1	0	0	0	0	0	0	$94.26	$123.98	$150.55	$477.52
6	8,588	55,718	2	2	0	0	0	0	0	0	0	$111.44	$120.23	$146.00	$450.88
7	8,328	64,046	1	1	1	1	1	0	1	1	1	$128.09	$116.59	$141.58	$1,264.90
8	8,076	72,122	2	2	0	0	0	0	0	0	0	$144.24	$113.06	$137.29	$467.82
9	7,832	79,954	1	1	1	0	0	0	0	0	0	$159.91	$109.65	$133.14	$474.81
10	7,595	87,549	2	2	0	0	0	0	0	0	0	$175.10	$106.33	$129.12	$483.76
Total															$5,559.65

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements									Other Engine Maintenance	Non-engine Maint	Tire Costs	Total Costs
			Engine Oil	Oil Filter	Fuel Filter	Air Filter	Spark Plugs	PCV Valve	Timing Chain	Front Pads	Front Rotors				
1	12,518	12,518	2	2	0	0	0	0	0	0	0	$25.04	$175.25	$212.80	$486.30
2	12,139	24,656	2	2	1	0	0	0	0	0	0	$49.31	$169.94	$206.36	$534.33
3	11,771	36,428	3	3	1	1	0	0	0	1	0	$72.86	$164.80	$200.11	$814.97
4	11,415	47,843	2	2	1	0	0	0	0	0	0	$95.69	$159.81	$194.06	$558.27
5	11,070	58,913	2	2	0	0	0	0	0	0	0	$117.83	$154.98	$188.19	$534.22
6	10,735	69,648	2	2	1	1	1	0	1	1	1	$139.30	$150.29	$182.50	$1,387.33
7	10,410	80,058	3	3	1	0	0	0	0	0	0	$160.12	$145.74	$176.97	$628.16
8	10,095	90,153	2	2	1	1	0	0	0	1	0	$180.31	$141.33	$171.62	$833.85
9	9,790	99,943	1	1	0	0	0	0	0	0	0	$199.89	$137.06	$166.43	$539.99
10	9,494	109,436	2	2	1	0	0	1	0	0	0	$218.87	$132.91	$161.39	$640.44
Total															$6,957.85

Table B-4
Maintenance costs for City BEV 40

Low Mileage Case

Years	Annual Miles	Total Miles	Replacements		Other Maint	Tires	Total
			Front Pads	Front Rotors			
1	10,014	10,014	0	0	$140.20	$170.24	$310.43
2	9,711	19,725	0	0	$135.95	$165.09	$301.04
3	9,417	29,142	0	0	$131.84	$160.09	$291.93
4	9,132	38,274	0	0	$127.85	$155.24	$283.09
5	8,856	47,130	0	0	$123.98	$150.55	$274.54
6	8,588	55,718	0	0	$120.23	$146.00	$266.23
7	8,328	64,046	1	0	$116.59	$141.58	$462.17
8	8,076	72,122	0	0	$113.06	$137.29	$250.36
9	7,832	79,954	0	0	$109.65	$133.14	$242.79
10	7,595	87,549	0	0	$106.33	$129.12	$235.45
Total							$2,918.02

High Mileage Case

Years	Annual Miles	Total Miles	Replacements		Other Maint	Tires	Total
			Front Pads	Front Rotors			
1	12,518	12,518	0	0	$175.25	$212.80	$388.04
2	12,139	24,656	0	0	$169.94	$206.36	$376.30
3	11,771	36,428	0	0	$164.80	$200.11	$364.91
4	11,415	47,843	0	0	$159.81	$194.06	$353.87
5	11,070	58,913	0	0	$154.98	$188.19	$343.17
6	10,735	69,648	1	0	$150.29	$182.50	$536.79
7	10,410	80,058	0	0	$145.74	$176.97	$322.71
8	10,095	90,153	0	0	$141.33	$171.62	$312.95
9	9,790	99,943	0	0	$137.06	$166.43	$303.49
10	9,494	109,436	0	0	$132.91	$161.39	$294.31
Total							$3,596.52

Table B-5
Net Present Value of Life Cycle Cost Calculation for City Car CV

Present Value Calculation—Based on ARB Vehicle 25

Gasoline City Car

Discount rate:	8%
Gasoline, price per gallon	$1.75
ICE component cost:	$60
Miles per gallon	45
Inflation rate:	1.03

Low case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	10,014	$0	$1.750	$389	$404	$793
2	9,711	$0	$1.803	$389	$425	$814
3	9,417	$0	$1.857	$389	$449	$838
4	9,132	$0	$1.912	$388	$765	$1,153
5	8,856	$0	$1.970	$388	$537	$925
6	8,588	$0	$2.029	$387	$523	$910
7	8,328	$0	$2.090	$387	$1,510	$1,897
8	8,076	$0	$2.152	$386	$575	$962
9	7,832	$0	$2.217	$386	$601	$987
10	7,595	$0	$2.283	$385	$631	$1,017
Total	87,549	$60		$3,874	$6,422	$10,356
NPV of total		$60		$2,601	$4,138	$6,799
$ per mile		$0.001		$0.030	$0.047	$0.078

High case miles (gasoline)

Year	Mileage	Components	Gasoline Price	Fuel	Maintenance	Total
0	0	$60				$60
1	12,518	$0	$1.750	$487	$486	$973
2	12,139	$0	$1.803	$486	$550	$1,037
3	11,771	$0	$1.857	$486	$865	$1,350
4	11,415	$0	$1.912	$485	$610	$1,095
5	11,070	$0	$1.970	$485	$601	$1,086
6	10,735	$0	$2.029	$484	$1,608	$2,092
7	10,410	$0	$2.090	$483	$750	$1,233
8	10,095	$0	$2.152	$483	$1,026	$1,508
9	9,790	$0	$2.217	$482	$684	$1,166
10	9,494	$0	$2.283	$482	$836	$1,317
Total	109,436	$60		$4,842	$8,016	$12,919
NPV of total		$60		$3,252	$5,201	$8,512
$ per mile		$0.001		$0.030	$0.048	$0.078

Table B-6
Net Present Value of Life Cycle Cost Calculation for City BEV 40 (low mileage case)

Discount rate:	8%
Battery cost, $ per kWh:	$257
Pack capacity, kWh:	9
Energy Storage System Cost	$4,389
Incremental Vehicle Costs	-$470
Total Incremental Costs	$3,919
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$1
Electricity Price per kWh	$0.05
Fuel Economy, kWh per mile	0.200
Charger Efficiency	82%
Inflation rate:	1.03

Year	Mileage	Pack Cost	Other Costs	Electric Price	Fuel	Maintenance	Total
0	0	$4,389	-$470				$3,919
1	10,014	$0	$0	$0.050	$100	$310	$411
2	9,711	$0	$0	$0.052	$100	$310	$410
3	9,417	$0	$0	$0.053	$100	$310	$410
4	9,132	$0	$0	$0.055	$100	$309	$409
5	8,856	$0	$0	$0.056	$100	$309	$409
6	8,588	$0	$0	$0.058	$100	$309	$408
7	8,328	$0	$0	$0.060	$99	$552	$651
8	8,076	$0	$0	$0.061	$99	$308	$407
9	7,832	$0	$0	$0.063	$99	$308	$407
10	7,595	-$77	$0	$0.065	$99	$307	$400
Total	87,549	$4,382	-$470		$996	$3,332	$8,240
NPV of total		$4,385	($470)		$669	$2,216	$6,800
$ per mile		$0.050	-$0.005		$0.008	$0.025	$0.078

Table B-7
Net Present Value of Life Cycle Cost Calculation for City BEV 40 (high mileage case)

Discount rate:	8%
Battery cost, $ per kWh:	$364
Pack capacity, kWh:	9.5
Energy Storage System Cost	$5,543
Incremental Vehicle Costs	-$470
Total Incremental Costs	$5,074
Pack life, years:	10
Replacement pack cost:	NA
Pack salvage value, $ per kWh:	$232
Electricity Price per kWh	$0.05
Fuel Economy, kWh per mile	0.200
Charger Efficiency	82%
Inflation rate:	1.03

Year	Mileage	Pack Cost	Other Costs	Electric Price	Fuel	Maintenance	Total
0	0	$5,543	-$470				$5,074
1	12,518	$0	$0	$0.050	$125	$388	$513
2	12,139	$0	$0	$0.052	$125	$388	$513
3	11,771	$0	$0	$0.053	$125	$387	$512
4	11,415	$0	$0	$0.055	$125	$387	$511
5	11,070	$0	$0	$0.056	$125	$386	$511
6	10,735	$0	$0	$0.058	$124	$622	$747
7	10,410	$0	$0	$0.060	$124	$385	$510
8	10,095	$0	$0	$0.061	$124	$385	$509
9	9,790	$0	$0	$0.063	$124	$384	$508
10	9,494	-$305	$0	$0.065	$124	$384	$203
Total	109,436	$5,238	-$470		$1,245	$4,097	$10,110
NPV of total		$5,402	($470)		$836	$2,741	$8,510
$ per mile		$0.049	-$0.004		$0.008	$0.025	$0.078

C

COSTS TO THE OEM FOR HEVS, PHEVS, AND CITY EVS

Introduction

Four vehicle designs are compared and contrasted in this appendix. The four vehicle designs are:

- A conventional vehicle (CV) with an internal-combustion engine (ICE) that served as baseline for the comparisons of vehicle attributes
- A parallel hybrid with a small battery for power assist and regenerative braking but no plug-in capability and no all-electric range (HEV 0)
- A parallel hybrid that can operate like an HEV 0 but also has plug-in capability and a battery of sufficient capacity to provide about 20 miles of all-electric range (PHEV 20)
- A battery electric vehicle with a battery of sufficient capacity to provide about 40 miles of all-electric range (BEV 40)

To study the above HEV designs, two platforms were considered. These include:

- A mid-size vehicle based upon a 2003 Ford Taurus LX with a 3.0L V-6 engine
- A full-size SUV based upon a 2003 Chevrolet Suburban 1500LS 4WD with a 5.3L V-8 engine

To study the city car design, a 36 kW gasoline-powered city car was designed. This is an original design with additional power for the American market. A gasoline-powered city is not sold in the U.S.

This appendix covers the details on cost to the OEM and willingness to pay more for HEVs and PHEVs to support section 4.

Cost to the OEM Methodology

In Sections 4 and 5, the cost-based price to the consumer (retail price equivalent) using a methodology developed by the Argonne National Lab for the HEVWG was presented. In order to calculate the RPE, the cost at the gate to the OEM was calculated, and then overhead costs as well as dealer and manufacturer profits, were added. This section looks only at the cost to the OEM at the gate, and whether these costs can be recouped.

Profits can vary tremendously among the three platforms studied in this report – full-size SUV, mid-size car, and city car (which is smaller than a subcompact). As profits are not a cost, they are excluded from this chapter. The indirect costs that are part of the OEM and dealer mark-up are also excluded. It is assumed that these costs are the same for conventional vehicles, engine dominant HEVs, plug-in HEVs, and City EVs in the later part of this decade, and for the three very different platforms studied – city cars, full-size SUVs, and mid-size sedans. A more comprehensive effort should be taken to detail these indirect costs for different platforms and technologies. Appendix C-4 of the HEVWG 2001 report [R-1] details the indirect costs, which comprise production-related overhead (research and development engineering, depreciation and amortization, and warranty), corporate overhead (management costs, retirement, and health benefits), vehicle-sales-related costs (vehicle distribution, advertising, dealer support, and dealer margin) and profit.

CARB staff in its staff reports speaks separately about price and cost and recognizes that profits and cross-product line subsidies have a large impact on the final price.[83] Because it is very easy to mix cost and price and add profits into this type of analysis, this section only discusses cost to the OEM at the gate. In addition, the numbers in this study use the HEVWG 2001 and 2002 studies' ANL method for costs at the gate, which expect the following components to have been supplied to the OEM by outside suppliers:

- Traction motor
- Power electronics and inverter
- Battery pack modules

The component costs at the gate above include a partial mark-up applied by the outside vendor for production facilities, corporate overhead, and profits, but will also be partially marked up by the OEM to include other items such as dealer support, marketing, warranties, etc.

There are a number of reasons for not using an estimate of retail price (RPE) and instead using cost at the gate to the OEM. Profits to the carmaker on SUVs can exceed $10,000 [R-9, R-10], while profits on compact and subcompact cars can be very low or negative. Dealer profits similarly are high on SUVs and low on compact and subcompact cars. Corporate goals (image, capturing new markets, gaining market share) and CAFE compliance further make cost-based pricing analysis problematic. A cost-at-the-gate analysis eliminates these biases. HEV 0s, PHEV 20s and BEV 40s may have some higher indirect costs in the early years such as training dealers, higher marketing costs, but these products also bring important non-quantifiable benefits mentioned above that are very important to carmakers and dealers. [R-9, R-10].

Cost to the OEM at the Gate

Table C-1, Table C-2 and Table C-3 show the cost at the gate to the OEM using the ANL methodology in the HEVWG 2001 study and the high mileage PHEV 20 (which has a larger battery). In the later part of this decade, the HEV 0 battery modules are expected to be at or near the bottom of the cost curve or $400/kWh, but it is harder to predict where the HEV 20 modules

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[83] page 95 and 102 of August 7, 2000 staff report [R-5].

will be on their cost curve. Thus several cases are shown including the lowest cost case on the right, which uses a smaller battery pack that has fewer lifetime miles.

Table C-1
Mid-size car cost at the gate using the ANL cost-method

Vehicle Type	**CV**	**HEV 0**	**PHEV 20**			
Battery Module Cost $/kWh	—	$400	$480	$400	$320	$320
Mileage Assumption	Both	Both	High	High	High	Low
Engine Power, kW	127	67	61	61	61	61
Engine Type	V-6	I-4	I-4	I-4	I-4	I-4
Traction motor, kW	—	44.3	51.3	51.3	51.3	51.3
Engine + Exhaust	$2,357	$1,444	$1,370	$1,370	$1,370	$1,370
Transmission	$1,045	$625	$625	$625	$625	$625
Accessory Power	$210	$300	$300	$300	$300	$300
Electric Traction	$40	$1,390	$1,542	$1,542	$1,542	$1,542
On Vehicle Charging System	—	—	$460	$460	$460	$460
Subtotal cost less Battery	$3,652	$3,759	$4,297	$4,297	$4,297	$4,297
Incremental subtotal cost less Battery		$107	$645	$645	$645	$645
Battery, kWh	—	2.91	8.00	8.00	8.00	5.88
Battery Module Costs		$1,164	$3,840	$3,200	$2,560	$1,882
Other Battery Costs	$30	$742	$809	$809	$809	$781
Total	$3,682	$5,665	$8,946	$8,306	$7,666	$6,960
Incremental Cost at Gate vs CV	—	$1,983	$5,264	$4,624	$3,984	$3,278
Incremental cost at Gate vs HEV 0	—	—	$3,281	$2,641	$2,001	**$1,295**

Table C-2
Full-size SUV cost at the gate using the ANL cost-method

Vehicle Type	**CV**	**HEV 0**	**PHEV 20**			
Battery Module Cost $/kWh	—	$400	$480	$400	$352	$352
Mileage Assumption	Both	Both	High	High	High	Low
Engine Power, kW	212	145	115	115	115	115
Engine Type	V-8	V-8	V-6	V-6	V-6	V-6
Traction motor, kW	--	65.3	98	98	98	98
Engine + Exhaust	$3,745	$2,992	$2,224	$2,224	$2,224	$2,224
Transmission	$1,200	$800	$800	$800	$800	$800
Accessory Power	$244	$339	$339	$339	$339	$339
Electric Traction	$50	$1,847	$2559	$2,559	$2,559	$2,559
On Vehicle Charging System	—	—	$460	$460	$460	$460
Subtotal cost less Battery	$5,239	$5,978	$6,382	$6,382	$6,382	$6,382
Incremental subtotal cost less Battery		$739	$1,143	$1,143	$1,143	$1,143
Battery, kWh	—	5.19	11	11	11	9.3
Battery Module Costs	—	$2,076	$5,280	$4,400	$3,872	$3,274.
Other Battery Costs	$30	$773	$848	$848	$848	$825
Total	$5,269	$8,827	$12,510	$11,630	$11,102	$10,481
Incremental Cost at Gate vs. CV	—	$3,558	$7,241	$6,361	$5,883	$5,212
Incremental cost at Gate vs. HEV 0	—	—	$3,683	$2,803	$2,275	**$1,654**

Table C-3
City car cost at the gate using the ANL cost-method

Vehicle Type	**CV**	**BEV 40**		
Battery Module Cost $/kWh	--	$400	$320	$320
Mileage Assumption		High	High	Low
Engine Power, kW	36	—	—	—
Engine Type	I-3	—	—	—
Traction motor, kW	—	27	27	27
Engine + Exhaust	$1,064	$0	$0	$0
Transmission	$800	$500	$500	$500
Accessory Power	$176	$261	$261	$261
Electric Traction	$30	$1,013	$1,013	$1,013
On Vehicle Charging System	—	$460	$460	$460
Subtotal cost less Battery	$2,070	$2,234	$2,234	$2,234
Incremental subtotal cost less Battery	—	$214	$214	$214
Battery, kWh	—	9.5	9.5	9
Battery Module Cost	—	$3800	$3040	$2880
Other Battery Costs	$30	$818	$818	$812
Total	$2,100	$6,852	$6,092	$5,926
Incremental Cost at Gate vs. CV	—	$4,752	$3,992	$3,826

Cost Benefit to OEM - Consumer Willingness to Pay for Fuel Economy and Other Benefits

ARB staff in their Jan 10, 2003 staff report [R-8, Page 5-3] modified their HEV 0 cost to the OEM analysis by subtracting any benefits to the OEM. Specifically, ARB staff methodology ends up with a negative $300 incremental cost in 2012 and beyond, because a $1000 willingness-to-pay for HEV attributes is subtracted from their $700 incremental cost estimate for an HEV 0. ARB staff explains that HEV 0s have attributes such as better performance, fuel economy, or in some cases 4-wheel drive that consumers will pay more for. This results in an OEM being able to recoup some or all of their incremental cost.

The $1000 willingness-to-pay more for an HEV 0 is based on an HEV 0 with a 30% increase in fuel economy. ARB staff explains this is based on their estimate that for every 10% increase in fuel economy an HEV 0 using $1.75 per gallon gasoline, the consumer is willing to pay $320 more for the HEV than for its conventional counterpart. ARB staff is being more conservative than a separate analysis cited by OEMs which estimates for 10% increase in fuel economy at $1.30 per gallon gasoline for an HEV 0, the consumer is willing to pay $350 more for the HEV 0 than for its conventional counterpart.

The HEVWG study [R-1] included a market assessment component developed collaboratively with automotive OEMs and a respected market analysis firm found consumers willing to pay about $2300 more for an HEV 0 (that had 45% better fuel economy[84]) than its gasoline counterpart[85] Using ARB's methodology, this translates into consumers being willing to pay $511 more for every 10% increase in fuel economy. The same study found consumers willing to pay $4,000 more for a PHEV 20 (that had 90-115%[86] better fuel economy) than its gasoline counterpart. Using ARB's methodology, this translates into consumers being willing to pay $353-$443 more for every 10% increase in fuel economy. Put in other terms, the collaborative ARB and automaker study [R-1] found a willingness to pay $1,800 more for the PHEV 20 mid-size car than the HEV 0.

Based on this prior analysis, this study takes a more conservative approach than that in Reference 1, estimating a consumer would pay $400 more for each 10% increase in fuel economy in a mid-size PHEV 20 and $500 more for each 10% increase in fuel economy in a mid-size HEV 0.

For full-size sport utility vehicle SUVs using data from the same collaborative study [R-6], this study estimates that a consumer would pay about $500 more for each 10% increase in fuel economy in a full-size SUV PHEV 20 and $600 more for each 10% increase in fuel economy in a full-size SUV HEV 0 [87]. Interestingly, diesel engine full-size SUVs or trucks can cost an OEM $4,000 more than their gasoline counterparts and about $2,000 more for a diesel small SUV that achieves about 40% better fuel economy than its gasoline counterpart.[88]

In the case of vehicles that plug-in, a consumer's willingness to pay more is not just fuel economy based, but appears to be based on a wide range of attributes, including less maintenance, avoiding gas stations, convenience of having a full battery every morning, reducing air pollution, petroleum and global warming as well as less noise/vibration, improved acceleration, and features such as 120V appliances or pre-heat/pre-cool with the engine off [R-1].

For City EVs, the fuel economy benefit is 271% greater than a 45-mpg gasoline city car.[89] The ARB methodology does not work in this case, as assuming $350 for every 10% increase in fuel

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[84] Reference 1 table A-1

[85] Reference 1, Table A-7. A CV at $18,984 achieves 54% market potential and an HEV 0 at $21,373 achieves 46% market potential.

[86] Reference 1, Tables A-1 and B-3 bound the different ways of calculating PHEV 20 mpeg.

[87] For example, at $37,650 a CV attains 54% market potential versus 46% for a $42,040 HEV 0 SUV that gets 50% better fuel economy, which translates into $860 for every 10% increase in fuel economy. A $43,580 PHEV 20 SUV that gets about 110% better fuel economy than the CV translates into about $530 for every 10% increase in fuel economy.

[88] Los Angeles Times, "Diesels Fueling Renewed Interest," Feb. 16, 2003, page C-1.

[89] Based on a 0.20 kwh/mi electric fuel economy which equals 167 mpeg using a petroleum equivalence factor of 33.44 kWh/gallon of gasoline.

economy would make the willingness to pay number too high. There are studies, however, showing willingness for consumers to pay more for EVs given their fuel and maintenance savings, "fun-to-drive" attributes, and societal benefits.[90] Taking all this into account, this study assumes at a range of willingness to pay from $2,000 to $3,000 more than the gasoline city car.

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[90] To cite a few: Reference 10: Green Car Institute and Dohring Company, *The Current and Future Market for Electric Vehicles,* September 2000*; EV Vision 2007*, EPRI report TR-109194 October 1997; Turrentine, T. & Kurani, K. *The Household Market for Electric Vehicles* ITS-UC Davis, May 1995 and; Irwin, K. *Marketing Electric Vehicle Technology: What Research Reveals* 90th Air & Waste Management Association, June 1997.

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E

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

Export Control Restrictions

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