Battery Electric Vehicles: An Assessment of the Technology and Factors Influencing Market Readiness

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Abbreviations

BEV – battery electric vehicle
EV – electric vehicle
ZEV – zero emission vehicle
ICEV – internal combustion engine vehicle
CARB – California Air Resources Board
GM – General Motors
NEV – neighborhood electric vehicle
CEV – city electric vehicle
SUV – sport utility vehicle
Wh – watt hour
MJ - megajoule
L - liter
kWh –kilowatt hour
kW - kilowatt
IC – internal combustion
DC – direct current
AC – alternating current
RPM – revolutions per minute
PM – permanent magnet
Li-ion – lithium ion battery
NiMH – nickel metal hydride battery
HEV – hybrid electric vehicle
USABC - United States Advanced Battery Consortium
BMS – battery management system
SOC – state of charge
Ah – amp hour
OEM – original equipment manufacturer
PHEV – plug-in hybrid electric vehicle

1. INTRODUCTION AND BACKGROUND

In 1990, General Motors (GM) announced the development of the *Impact,* a concept battery-powered electric vehicle (BEV). BEVs use electric motors to convert the electrical energy in to mechanical work to power the wheels. At the unveiling of the Impact, GM announced that they intended to manufacture a marketable version of the *Impact* prototype. GM's announcement encouraged the California Air Resources Board (CARB) to adopt a set of new vehicle emission regulations, which included the Zero Emission Vehicle (ZEV) Mandate that required the large auto companies manufacture and have available for sale ZEVs in 1998. The sales of ZEVs were to be 2% in 1998 increasing to 10% by 2002. In response to the Mandate, the auto companies began to design and test electric vehicles. Only GM with the EV-1 and Honda with the EV Plus produced a purpose-built BEVs. The other auto companies proceeded with the release of BEV conversions of conventional vehicle models, such as the *Ford Ranger EV* and *Toyota RAV-4 EV*. Most of the auto companies followed GM's lead of leasing but not selling their BEVs to consumers. Only Toyota with the RAV-4 EV sold vehicles to the public. Table 1 is a list of the BEVs that were made available in California following the enactment of the ZEV Mandate.

Table 1 - BEVs built by OEMs and marketed in California in response to the ZEV Mandate.

Make	*Model*	*Year(s)*	*# Produced*	*Cost ($)*
GM/Saturn	EV1	1996-2003	1,000	40,000
Chrysler	EPIC	1997-2000	350	fleet only
Honda	EV-Plus	1997-1999	300	53,000
Toyota	RAV4 EV	1997-2002	1,250	40,000
Chevrolet	S10 EV	1998	100	fleet only
Ford	Ranger EV	1998-2002	1,500	50,000
Nissan	Altra EV	1998-2000	133	fleet only
Hyundai	Santa Fe EV	2005	15	fleet only

During the period from 1996 to 2002, approximately 4,000 vehicles were made available to the California public for lease. That represents only about 0.01% of the statewide personal vehicle sales during that period. Following a lawsuit filed against California by the three major U.S. auto manufacturers, the requirements of the ZEV Mandate were suspended by CARB in 2002. Shortly thereafter, nearly all the manufacturers began to terminate lease agreements and repossessed and destroyed the vehicles. Only Toyota allowed consumers to keep their vehicles. One account of the issues related to the recall of the BEVs can be found in the film *Who Killed the Electric Car?* Another account of the story of the *EV-1* is available in the book that chronicled its development, *The Car That Could.*

Many questions and much debate exists regarding why the auto manufacturers recalled and destroyed the BEVs even though most of the vehicles were still operating well and the owners were happy with them. One possible reason is that after the automakers concluded that they could not mass market electric vehicles, they decided it was in their best interest to remove the vehicles from public view. The auto companies and many other experts were, and still are, of the opinion that even after continued development battery technology could not and would not meet consumer demands for vehicle range and recharge time, battery life, and cost. High battery cost was seen to be a particularly large obstacle to commercializing BEVs. Hence, regardless of the

BEV's potential social and environmental appeal, the auto companies concluded that BEVs were not a viable business investment and shifted their emphasis to the development of other clean vehicle technologies.

Today, none of the major automobile manufacturers in the United States is selling BEVs and they have shown little interest in doing so in the foreseeable future. The only BEVs available for sale or lease are neighborhood electric vehicles (NEVs) that have a maximum speed of 25 mph and are considered niche vehicles. These vehicles earn ZEV credits for the manufacturers, but are not considered candidates for the mass car market. A review of the current situation regarding the ZEV Mandate and ZEV credits is given in Reference 1.

In light of this recent history, the objective of this report is to assess the current status of BEV technologies and the future market potential for purpose-built BEVs. Of particular importance in this regard is the present and projected status of battery technology and battery cost in mass production, especially that of lithium batteries, which have undergone rapid development in recent years.

2. ELECTRIC VEHICLE DESIGN CONSIDERATIONS

This report will consider passenger cars, light-duty trucks, vans, and sport utility vehicles (SUV). Medium and heavy-duty vehicles will not be considered as they are not, except for transit buses, candidates for battery powered electric drivelines. The purpose of this section is to describe the various design options that influence the energy use of vehicles and to explain how they contribute to the efficient operation of the vehicle.

2.1 Electric vehicle functionality

It is unlikely that battery electric vehicles will be comparable in every aspect to conventional ICE vehicles. Significant tradeoffs exist where certain aspects of BEVs fare poorly when compared with conventional vehicles while other aspects of BEVs are better. As a result, there is considerable debate concerning the functionality required of electric vehicles if they are to be marketed in large numbers (at least 10-15% of total auto sales as required by the ZEV Mandate). It is often assumed that most electric vehicles would be sold in urban areas and be used for commuting and local/regional travel. To be of maximum utility to the owners for regional use, the vehicles would need to be freeway worthy with top speeds of at least 65 mph. Such BEVs are often referred to as full-function EVs. Smaller markets exist for neighborhood electric vehicles (NEVs) which have legal top speeds of only 25 mph.

Electric batteries are bulky and heavy compared to gasoline, and require a longer time to recharge. Consequently, BEVs tend to underperform compared to conventional vehicles with respect to vehicle range and refueling time. Designing a fully functional BEV requires compromises in passenger comfort (spacious vehicle and large trunk space) and operating convenience (convenient refueling) although to reach mass markets, these compromises should be minimized. For a long distance vehicle, where range is paramount, consumers may be willing to sacrifice some interior space.

However, there are BEV attributes that may be more attractive to consumers, such as the possibility of home refueling/recharging, which eliminates trips to the gas station, quiet driving, excellent acceleration, and environmental attractiveness (zero emissions) and independence from oil use (Heffner and Kurani 2006). These benefits, however, may not sway consumers who are looking for a general purpose replacement vehicle.

Figure 1 classifies daily driving distance (percentage of trips) into a histogram and also displays the percentage of daily driving that is below a certain distance (utility factor). A vehicle range of 100 miles appears to cover approximately 75% of all daily driving, based upon the 1995 survey data [35].

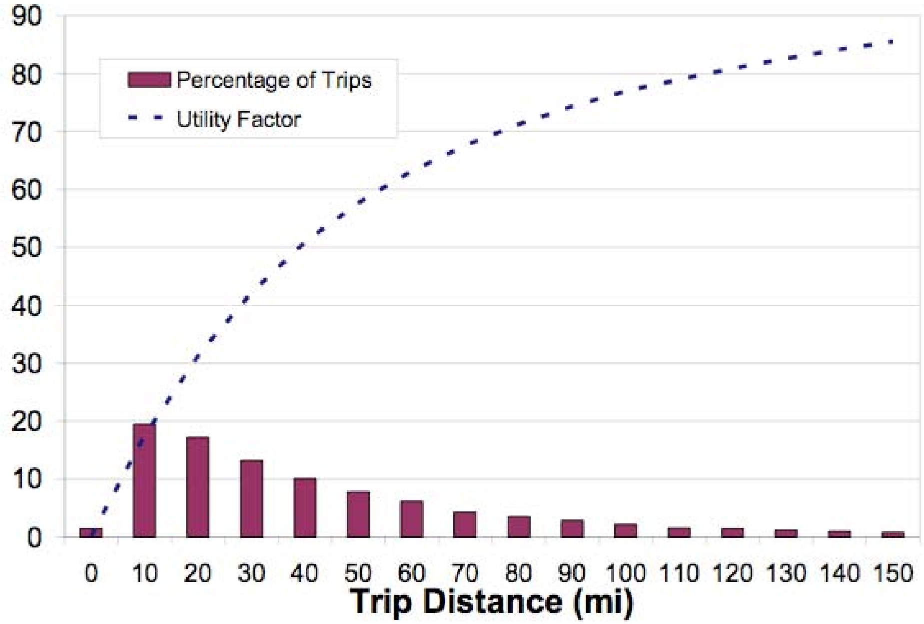

Figure 1 – Distribution of daily driving distances [35].

2.2 Electric vehicle weight and road load

The energy density of gasoline (9400 Wh/L, 34 MJ/L) is nearly two orders of magnitude higher than the best battery (100-150 Wh/L, 0.36-0.54 MJ/L). For this reason, ICEVs are generally designed with less attention to energy efficiency than is the case for BEVs. Vehicle characteristics such as weight, aerodynamic drag and rolling resistance are often not given a high priority in conventional vehicle design. However, for EVs, careful consideration of weight, aerodynamics and powertrain efficiency is no longer a luxury, but rather is absolutely necessary to achieve the driving range and vehicle performance expected by car buyers. A number of BEV prototypes and design and modeling studies have investigated the reduced energy usage that is possible for BEVs due to reductions in weight, aerodynamic drag, rolling resistance and powertrain efficiency [2-10].

2.3 Electric vehicle range, recharging and performance

Electric vehicles with ranges between 50 miles and 200 miles have been designed and built using various types of batteries. The short range vehicles use lead-acid batteries and the long range vehicles use lithium-ion batteries, with vehicles using nickel metal hydride batteries having intermediate ranges. Building vehicles with larger range would be very expensive as well as reduce vehicle cargo space. The acceleration performance of an electric vehicle is primarily dependent on the power (kW) of the motor and the weight of the vehicle. Electric motors have excellent low-speed torque characteristics and consumers generally like the feel and responsiveness of electric vehicles. Vehicles have been built with 0-60 mph acceleration times as low as 5 seconds, but in general the acceleration times are 10-12 seconds. The recharge time of the battery in an EV is primarily dependent on the electrical characteristics (voltage and power) of the charger and the electrical source to which it is attached. Most batteries can be recharged in less than 30 minutes when the proper charger and electrical source are available, though longer charge times are more typical due to constraints on charging circuits.

2.4 Powertrain configurations and components

The driveline configurations of battery electric vehicles (BEVs) are relatively simple in that they have only a few components. The drivelines consist primarily of an electric motor, power electronics (including charge controller and DC/AC inverter), and a battery pack (see Figure 2). The battery pack for an EV is large (weighing at least 200 kg), since it is the primary energy storage unit and must provide all the energy needs (propulsion and auxiliaries) of the vehicle. The electric motor(s) provide all of the wheel torque to accelerate the vehicle and for energy recovery during regenerative braking. The motor and electronics must be sized to meet the maximum torque/power required to accelerate/brake the vehicle and to maintain the maximum speed of the vehicle on a grade. The various components in the electric driveline are discussed in the next sections.

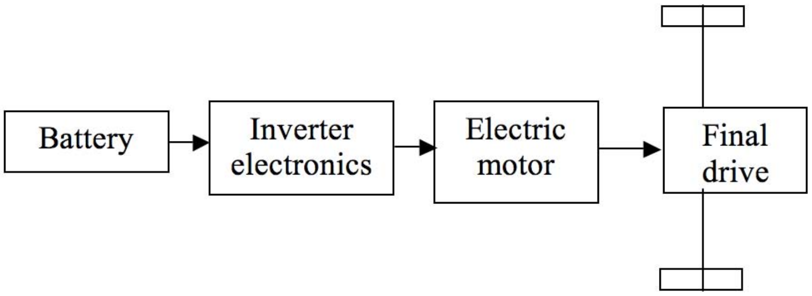

Figure 2 – Schematic of driveline for battery electric vehicles

3. BEV TECHNOLOGIES AND PERFORMANCE

The electric drive unit consists of the motor, power electronics, and microcomputer based controller needed to meet the time-varying power demands of the vehicle.

3.1 Electric Motors and electronics

3.1.1 Motors

An electric motor is used to convert the electrical energy from the battery to mechanical energy to power the vehicle. Electric motors are efficient converters of electrical energy into mechanical work, with efficiencies between 70-95% depending upon the operating parameters. As shown in Figure 2, the torque from the electric motor is applied to the drive shaft of the vehicle and the wheels in many cases without a multi-gear ratio transmission. Electric motors have higher power density (power per unit weight and volume) than internal combustion engines and advantageous low-speed torque characteristics compared to internal combustion engines. The result is the smooth, rapid acceleration common of electric vehicles. In addition, motors can be used to recover braking energy, in the form of electricity from regenerative braking which can be stored in the battery and reused.

There are a number of different types of electric motors (Figure x) that have been used in electric vehicles. These include series and separately excited DC motors and induction, permanent magnet, and switch reluctance AC motors. Extensive information and data on electric motors for electric vehicles are given in **References 11-13**. The power electronics take the DC output of the battery and convert it to the form needed by the various motor options over their complete range of torque and speed (RPM).

Table 2 – Classification of electric motors used in EVs [11].

Commutatorless	PM brushless DC	
	Switched Reluctance	
	PM Hybrid	
	Synchronous	Reluctance
		PM rotor
		Wound rotor
	Induction	Squirrel cage
		Wound rotor
Commutator	Separately excited	PM excited
		Field excited
	Self excited	Shunt
		Series

DC motors, both series and separately excited, utilize brushes for commutation and power electronics is used to control the effective voltage applied to the armature and field windings of the motors. The lowest cost electric drive units are those using series DC motors, but they are applicable only in low speed vehicles. Separately excited DC motors can be used in higher speed vehicles, but most EVs at the present time use one of the types of AC motors. The brushes in the DC motors limit their maximum RPM and to some extent the maximum system voltage and require periodic maintenance.

In general, the AC motor systems are smaller, lighter, more efficient and lower cost than the DC systems especially as the power requirements for the systems have increased. High performance, high speed electric vehicles have been designed and built using both induction and permanent magnet types of AC electric motors. At the present time, the permanent magnet type motor seems to be the choice for small and moderate power (25-150 kW) systems used in passenger cars and the induction motor type is the choice for large vehicles like heavy duty trucks and transit buses. The permanent magnet (PM) motors tend to be smaller and easier to control than the induction motors at moderate powers, but the induction motors are more durable and lower cost when the power required is high (>200 kW).

A typical efficiency map for an induction AC motor is shown in Figure 3. Note that the efficiency varies significantly with torque and RPM, that efficiency is higher at low speed and high torque while efficiency is lower at higher speed, and that no single value of efficiency is applicable for a motor in a vehicle operated over a driving cycle. Simulations of electric vehicles using both induction and PM motors have been performed [11]. For all driving cycles, the energy usage of vehicles using the PM motors (5.1-7.1 km/kWh) are lower than those using the induction motors (4.6-6.0 km/kWh). The differences vary with driving cycle, but are in the range of 10-20% with the largest differences being on city cycles (stop/go driving). The improved efficiency with the PM motors would translate directly into longer driving range for the same size (kWh) battery.

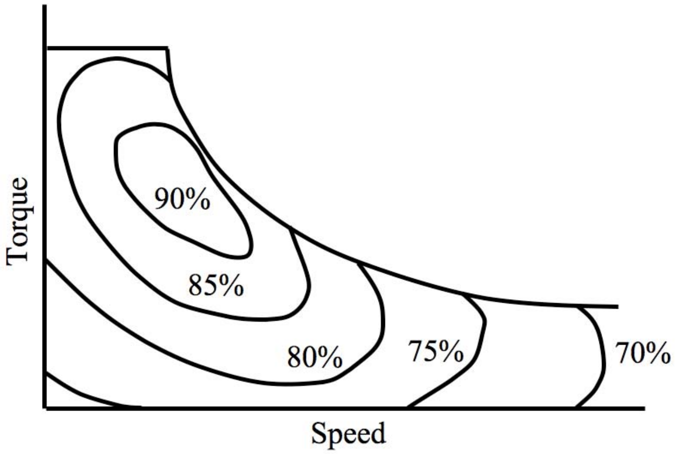

Figure 3 – Representative efficiency map for an induction motor.

3.1.2 Power Electronics

The peak power rating of electric drivelines used in electric vehicles has increased greatly in the last ten years. This is due primarily to the improved performance (current and voltage limits) of the semiconductor switching devices used in the power electronics. The DC/AC inverter in the driveline system includes at least six switching devices to control the time varying voltage fed from the battery to the electric motor. The technology improvements in the switching devices has not only improved their performance, but lowered their cost and increased reliability significantly. The efficiency of the power electronics is in the range of 95-98% meaning that most of the losses in the electric driveline are in the electric motor. In addition, much progress has been made in developing and implementing new control algorithms for the various types of AC motors that permit motor operation at high efficiency over a large portion of the motor torque/RPM map [11]. Using present motor and power electronics technologies, average electrical to mechanical work efficiencies of 85-90% over typical driving cycles are not uncommon.

3.2 Battery technologies

One of the inherent limitations of electric vehicles is their limited range due to the relatively low energy density of batteries. Based on real world experience with the ZEV Mandate BEVs, battery cost and limited vehicle range (i.e. energy density) were the primarily deterrents to the mass marketing of electric vehicles. Thus, a better understanding of the status of battery technology, including the most promising types and their cost, durability and performance, is a critical factor in assessing the prospects for battery electric vehicles.

3.2.1 Battery types

Many different types of batteries have been considered and developed for electric and hybrid vehicles over the last thirty years. At the present time, the battery types being considered and developed for electric vehicles are relatively few, namely **lead-acid, nickel metal hydride, lithium-ion and lithium polymer, and sodium nickel metal chloride**. Each of these battery types have some advantages and disadvantages and unfortunately none of them are attractive in all respects for electric vehicles. In addition, there are trade-offs between energy density, power density, cycle life, and cost so that even for a particular type of battery, it is necessary to design the batteries for specific applications. And while there is no clear choice of the best battery for all BEVs, nickel metal hydride and lithium ion batteries are the most promising battery types under development for vehicle use. Most of the electric vehicles produced and sold/leased to date have used either lead-acid or nickel metal hydride batteries. A limited number of vehicles have used lithium-ion or sodium /nickel chloride batteries. Lead-acid batteries are used primarily in low-speed neighborhood EVs having a relatively short range (25-50 miles). Most of the electric vehicles sold/leased as part of ZEV Mandate (1995-2002) used nickel metal hydride and had a range of 80-120 miles.

3.2.2 General considerations for battery selection

The key requirements for the energy storage unit for a particular vehicle design are useable energy stored, peak power, and cycle and calendar life. These requirements must be met with a unit whose weight and volume are less than specified values based on packaging the driveline in the vehicle. Differences in battery performance have a large influence on the performance (acceleration and range) of vehicles that can be designed and produced using them. In addition, the cost and cycle life of the batteries have a large effect on the potential marketability of electric vehicles. Whether a particular type of battery is suitable for electric vehicles depends on the desired characteristics of the vehicles in which it is to be used.

The energy density (Wh/kg, Wh/L) and power density (W/kg, W/L) characteristics of the various battery chemistries vary over a wide range as shown in Table 3. These differences in battery properties have a large influence on the performance (acceleration and range) of vehicles that can be designed and produced using them. In addition, the cost and cycle life of the batteries will have a large effect on the adoption electric vehicles. Different electric vehicle types have different characteristics and performance requirements, such as size, weight, acceleration performance and range, that determines which types of batteries are most appropriate.

Table 3 – Characteristics of electric vehicle batteries of various types

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 hr)
lead/acid	35-50	150-400	>80	500-1,000	0.6
nickel/cadmium	50-60	80-150	75	800	1
nickel/iron	50-60	80-150	75	1,500-2,000	3
nickel/zinc	55-75	170-260	65	300	1.6
nickel/metal hydride	70-95	200-300	70	750-1,200	6
iron/air	80-120	90	60	500	?
zinc/air	100-220	30-80	60	600	?
zinc/bromine	70-85	90-110	65-70	500-2,000	?
vanadium redox	20-30	110	75-85	?	?
sodium/sulfur	150-240	230	80	800	0
sodium/nickel chloride	90-120	130-160	80	1,200	0
lithium/iron sulfides	100-130	150-250	80	1,000	?
lithium-ion	80-130	200-300	>95	1,000	0.7

Table 4 - Characteristics of various technologies/types of batteries for use in vehicle applications

Battery Technology	**Vehicle type**	**Ah**	**V**	**Wh/kg At C/3**	**Resist mOhm**	**W/kg Match. Imped.**	**W/kg 95%eff.**	**Max. Useable SOC,**
Lead-acid								
Panasonic	HEV	25	12	26.3	7.8	389	77	28%
Panasonic	EV	60	12	34.2	6.9	250	47	----
NiMH								
Panasonic EV	EV	65	12	68	8.7	240	46	----
Panasonic EV	HEV	6.5	7.2	46	11.4	1093	207	40%
Ovonic	EV	85	13	68	10	200	40	----
Ovonic	HEV	12	12	45	10	1000	195	30%
Saft	HEV	14	1.2	47	1.1	900	172	30%
Lithium-ion								
Saft	HEV	12	4	77	7.0	1550	256	20%
Saft	EV	41	4	140	8.0	476	90	----
Saft	HEV	6.5	4	63	3.2	3571	645	20%
Shin-Kobe	EV	90	4	105	.93	1344	255	------
Shin-Kobe	HEV	4	4	56	3.4	3920	745	18%
A123	HEV	2.2	3.6	90	12			
Altairnano	EV	11	2.8	70	2.2	2620	521	60%
Altairnano	HEV	2.5	2.8	35	1.6	6125	830	60%

The three major requirements for a BEV battery pack are (1) providing adequate power, (2) providing adequate energy storage and (3) having an acceptable cycle life. The battery pack must provide power (kW) within the appropriate voltage range to the power electronics/motor to meet the demands of the driver. The battery pack must store sufficient energy (kWh) so that the vehicle can be driven a specified range (miles) before recharging. The power and energy storage requirements will impact the battery weight and volume and affect vehicle design. The battery must be able to be charged/discharged a specified number of cycles before the performance degrades and it needs to be replaced. The initial cost of the battery is also critically important, because if it is too high it will be difficult to market BEVs using that type of battery.

3.2.3 Battery performance and vehicle range

There are a number of ways to express battery performance. The simplest approach is to state the energy density (Wh/kg) and peak power density (W/kg) as shown in Table 3. This approach is good for showing the relative performance of various types of batteries, but does not show the detailed performance of a particular battery over different operating conditions. Detailed information of battery operation, such as the Ragone curve (Wh/kg vs. W/kg for constant power discharges), open circuit voltage and resistance vs. state-of-charge, capacity (Ah) vs. discharge current and temperature, and the charging characteristics of the battery at various rates and temperatures, are needed to assess the suitability of a particular battery for a specific electric vehicle application. Detailed information and performance data on a number of batteries is given in Handbook of Batteries, third edition, by D.Linden and T. Reddy [14].

As shown in Table 4, for a given battery chemistry, batteries can be designed with significantly different energy and power characteristics. For each battery type, there is a trade-off between energy density and power density with the higher power batteries having significantly lower energy density. In general, the battery pack in a BEV is sized by the energy storage requirement (kWh) and the power requirement (kW) is met even by the high energy density battery designs shown in the table.

The range of the electric vehicle is simply related to the energy use (kWh/mi) of the vehicle and the energy storage capacity (kWh) of the battery. The energy use depends primarily on the weight of the vehicle and its road load characteristics (aerodynamic drag, frontal area and rolling resistance). As discussed in Section 2, considerable care should be taken in the design of electric vehicles to reduce their weight and road load compared to conventional ICE vehicles of the same size and type. The results in the table also indicate the weight of batteries of various chemistries needed to attain a range of 100-150 miles. As expected, both the energy use and battery weight depend critically on the vehicle characteristics. For light-duty vehicles, useable energy storage of 15-40 kWh is needed to attain a range of 150 miles. This appears to be practical only for high energy density batteries like lithium-ion or chemistries having a useable energy density greater than 100 Wh/kg. Ranges in excess of 200 miles will require energy densities greater than 150 Wh/kg. Note that the United States Advanced Battery Consortium (USABC) has set a minimum goal of 150 Wh/kg for long term commercialization of electric vehicles and a longer term goal of 200 Wh/kg [10].

3.2.4 Battery cycle life and safety

In evaluating battery technologies for electric vehicles, cycle life is one of the key determinants of the economic viability of a particular battery technology. The cycle and calendar life depends critically on how the battery is operated, including the rate of discharge, how the battery is recharged and the average depth-of-discharge before recharge, and the temperature of operation of the battery. Of particular importance is the depth-of-discharge before recharge and the battery state of charge before each discharge cycle. As shown in Figure 4, the cycle life increases dramatically if the depth-of-discharge of the cycles is less than 50%. Both of these factors directly influence the useable energy and energy density of the battery and the range of a vehicle for a given weight of the battery. Hence careful attention should be given to the test procedures for both the battery capacity and cycle life tests.

Testing of batteries in laboratory and real-world situations seems to indicate that cycle life for nickel metal hydride batteries is good, lasting at least five years and 2000 cycles for deep discharges of 60-70% **[15]**. The cycle life of the lead acid batteries is much shorter, lasting only 2-3 years and 300-500 cycles. More testing is required before reliable cycle life information for lithium ion batteries is obtained.

The USABC has set a calendar life goal of 10 years and a cycle life goal of at least 1000 cycles to 80% depth-of-discharge as needed for commercialization of electric vehicles. Recent data indicate that the USABC battery life goals are attainable with nickel metal hydride batteries and are likely attainable with lithium-ion batteries

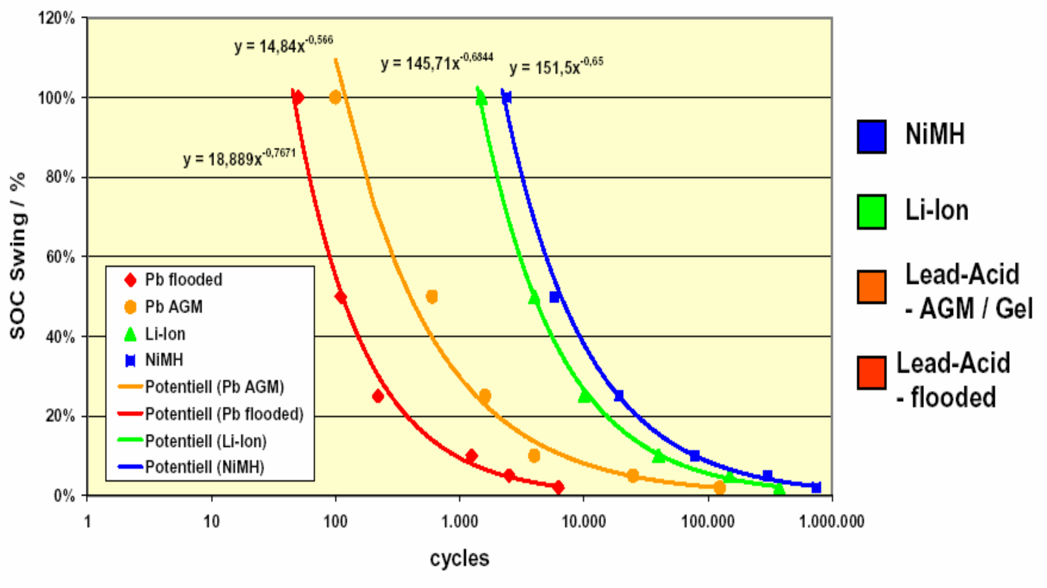

Figure 4 – Cycle life correlations for various types of batteries

Most battery packs have a battery management system (BMS) to monitor cell/module voltages and temperatures. In the case of lead-acid and NiMH batteries, the purpose of the BMS is to increase the life of the pack by assuring that the cells remain balanced and the temperatures do exceed a specified upper value. In the case of the lithium-ion batteries, the BMS is also needed to assure that the pack is operated safely as over-charging and/or over-discharging of the pack can result in a thermal runaway condition that can lead to an explosion and/or fire. Much of the current research on lithium-ion batteries stems from the desire to utilize electrode chemistries that do not have the inherent safety problems associated with graphite and NiCoAl electrode materials. Safety can be more of an issue with lithium batteries in BEV than in hybrid vehicles like the Prius because in the BEV the battery is deep discharged and fully charged after each cycle. One approach to minimizing the safety issue is to avoid deep discharges and full charges to the battery. However, this approach will reduce the useable energy and energy density of the battery.

3.2.5 Battery cost

The cost of the battery is a major issue for BEVs. While the experience with battery life has been encouraging, the experience to date on battery cost has not been equally encouraging. At the present time, large batteries for electric vehicles are very expensive, costing about $700-800/kWh for nickel metal hydride and even more for lithium-ion batteries. The cost of lead-acid batteries for BEVs is about $100/kWh. It is expected that the cost of the advanced batteries will decrease markedly when they are manufactured in high volume. A key question is how low the cost/price of the advanced batteries, in particular the lithium-ion batteries, will fall in high volume. Most projections of the cost of lithium-ion batteries are in the range of $300-500/kWh in mass production (hundreds of thousands of packs per year). In order to achieve comparable range to an ICE vehicle (~400 miles), BEV battery costs alone, assuming these cost projections, would be between $30,000 to $50,000 (see Figure 5).

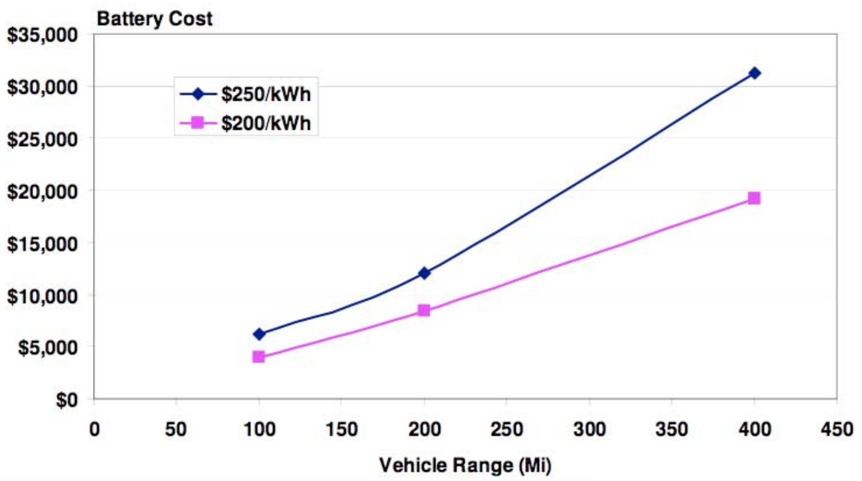

Figure 5 – Battery cost as a function of vehicle range [34].

Small cell (1-2 Ah) lithium-ion batteries are manufactured in very large volume (many million cells per year) and their cost seems to be about $1/Ah, which corresponds to $250/kWh. The USABC has set a selling price goal for advanced batteries of less than $150/kWh for long term commercialization of electric vehicles at a volume of 25,000 40 kWh packs per year. The long-term goal in larger volume production is $100/kWh. It is highly questionable whether these cost targets are attainable for either lithium-ion or nickel metal hydride. Note that these cost targets are for the selling price and include the cost of the battery management/monitor system and the box housing the battery in the vehicle.

It is important to realize that if vehicle range is increased by adding additional battery storage, the fuel economy of the vehicle (e.g. miles/kWh) will decrease due to the additional battery weight. For a vehicle with a 200 mile range, the batteries can weigh over 300 kg. Thus, the additional range achievable with additional batteries is non-linear, but declines as battery weight increases. Kromer and Heywood assign the highest long-term risk to electric vehicle commercialization to battery costs, as energy storage and the associated range issues lead to larger, more expensive battery backs. Barring unforeseen breakthroughs in battery materials and technology, meeting cost targets, such as the USABC goal, is “extremely challenging” [34].

3.2.6 Battery charging

Another of the concerns about the consumer functionality of battery electric vehicles has to do with battery recharging. In past BEVs, the time needed to recharge the battery was usually several hours due to the difficulty and expense of providing a high power battery charger and the required electrical source for connecting it to the grid. High-powered chargers exist that can speed up charging (from full depletion to 80-90% state of charge) to significantly less than an hour. This would allow EVs to be more competitive with ICEVs in terms of driving range and refueling times. However, large high power charging stations would be expensive and would require special equipment unavailable to most consumers. For example, to charge a 30 kWh battery in 10-15 minutes would require an electrical source of at least 150 kW (over 600 amps on a 240V circuit). Another disadvantage of fast charging is that the battery can not be fully charged at the high rate, which further limits the range of the BEV by 10-20%.

In addition, the battery pack must be designed with sufficient cooling to permit fast charging without overheating and damaging the battery. Heat generation in the battery is significantly higher during charging than during normal use in driving the vehicle. For most battery technologies, there is a relationship between cycle life, depth-of-discharge before recharge, and time to recharge. In general, battery cycle life is maximized for modest (i.e. slower) rates of recharge (greater than 1-2 hours) and moderate depths-of-discharge (50-60%). In addition, the maximum battery temperatures should be limited to 50ºC or lower. Fast charging does not appear to be a practical solution to the range limitation problem of BEVs.

3.3 Prototype/demonstration and production electric vehicles

Over the last 20-30 years, there have been many prototype/demonstration electric vehicles designed and built and a few production electric vehicles introduced into the market by small vehicle manufacturers. These vehicles represent a complete cross-section of vehicle types from large transit buses to small neighborhood electric cars. Many of these vehicles have used advanced electric driveline components, such as AC PM motors and associated power electronics, and advanced batteries. There is a considerable body of test data [16-20] from these vehicles, so there is not much uncertainty regarding the performance of electric vehicles using the advanced powertrain technologies and much evidence that the electric vehicles function in practice on the road as expected based on laboratory tests of the components and computer simulations of the vehicles using the laboratory component data as inputs.

Table 5 **-** Characteristics of selected battery electric vehicles

Model/ Manufacturer	**Type**	**Curb weight [kg]**	**Length/ width/height [cm]**	**Battery type/ kWh**	**Electric motor size [kW]**	**Range miles**	**Max. speed km/hr**
EV1/GM	Full	1350	432/178/130	NiMH/29	104	140	>120
EV Plus/ Honda	Full	1634	405/174/162	NiMH/30	49	100	>120
RAV4/ Toyota	Full	1560	398/169/167	NiMH/28	50	95	>120
Altra/Nissan	Full	2080	487/177/169	Li-ion/32	62	120	>100
Smart/Mercedes	Full	1380	357/172/160	NaAlCl/30	50	125	>120
Think/Ford	NEV	960	300/160/155	NiCad/12	12	50	40
E-com/ Toyota	CEV	790	279/148/160	NiMH /8	20	50	80
Hypermini/Nissan	CEV	840	266/148/155	Li-ion/10.5	24	60	80
Zenn/Feel good cars	NEV	510	258/138/139	VRLA lead-acid/7	8	35	40

Full - all roads and speeds
NEV- neighborhood EV
CEV- city EV

The characteristics of selected electric vehicles of various types are given in
Table 5. For each of the vehicles, information/data are presented describing the vehicle weight and road load, powertrain components, and performance (acceleration, top speed, and range). Many of the vehicles have been owned/leased by fleets and/or individuals and found to be reliable and able to meet their needs when forethought regarding the limited range of the vehicles is taken into account. Testing/use of these vehicles has indicated that from the reliability and

performance points-of-view, electric vehicle technology is close to market ready, if consumers are willing to accept the range, refueling and cost characteristics of BEVs.

3.4 Vehicle cost and ownership considerations

The cost of BEVs relative to conventional ICE vehicles of similar size and functionality is an important metric for understanding the viability of these vehicles and the likelihood of consumers to purchase them. Some additional initial price may be tolerable if the ownership or life cycle cost of the BEV is equal to or lower than that of the corresponding ICE vehicle. In addition, the functional utility of the BEV must be such that it meets the needs of the consumer for that vehicle. There have been a number of studies of both the cost and ownership considerations relative to BEVs [20-21]. These studies have indicated that there is a relatively small (10-20%), but still significant, potential market for BEVs if the price differential is not large. As would be expected, the potential market increases as the range of BEVs is greater and the price differential is smaller. Range considerations have been discussed in previous sections of the report. In this section, the price and life cycle costs of BEVs is considered.

The cost of the driveline in the BEV is simply the sum of the cost of the electric motor and power electronics and the cost of the battery system, including the battery management (BMS) and charger. Since the BEV is likely to be heavier than the baseline ICE vehicle because of the heavy battery pack, there is an additional cost in strengthening the chassis and suspension to carry the additional weight. If the weight of the BEV is reduced by light-weight material substitution that could also add to the cost of the vehicle. A detail study of the initial and life-cycle costs of BEVs is given in [Ref 22-24] which are incorporated into the present analysis.

The cost of the electric driveline components can be determined from the following relationships:

$$\text{OEM motor cost } = -111.3 + \left(127.7 \ln\left(P_{peak,kW}\right)\right)$$

$$\text{Power electronics cost } = 480 + \left(2.95 \ln\left(P_{peak,kW}\right)\right)$$

These relationships are valid for high production rates of 200,000 units/yr. The electric driveline cost depends on the power rating of the electric motor which is dependent primarily on the specified acceleration characteristics of the vehicle (ex. time to accelerate from 0-60mph). For most BEVs, the motor power is 30-100 kW.

The cost of the battery is dependent primarily on the specified range of the vehicle. In almost all cases, the battery is sized by the energy storage required (kWh) needed to meet the specified range. The energy storage requirement ($kWh_{bat,req}$) can be calculated from the energy consumption of the vehicle (kWh/mi) from the battery and the specified range.

$$\text{Energy storage required } kWh_{bat,req} = (\text{Range}) * (\text{kWh/mi})$$

For a compact car using batteries in the range of \$200-400/kWh [24], the OEM battery cost would be \$6000-\$12,000. Reducing the range of the vehicle and maintaining the same motor power (same acceleration performance) would mean that the required power density would increase in proportion to the reduction in range, which would require a redesign of the battery.

This would likely result in a reduction in energy density and higher cost. This is an example of the coupling between the vehicle performance and range and battery design and cost.

One factor in the marketability of BEVs is their cost relative to conventional ICE vehicles and whether the additional cost of the BEV can be recovered by the lower cost of the energy (electricity to recharge the batteries) to operate the vehicle. One metric of the economic competitiveness of the battery powered vehicles is the breakeven price of gasoline for which the life cycle cost of the BEV, including the differential price of the electric and ICE vehicles and the cost of the electricity to operate the BEV equals the cost of the gasoline to operate the ICE vehicle for 100,000 miles. The breakeven price of gasoline associated with vehicle price differentials between $6000 for compact vehicles to $9500 for large SUVs and $0.06/kWh electricity are between $2 and $3/gallon of gasoline and are consistent with other analyses [22]. It is important to note that the BEV in Table 6 has a 100 mile range. If a longer range were required, the breakeven gasoline price would be considerably higher.

Table 6- Battery powered vehicle cost characteristics for vehicles of various types

Vehicle types	**Energy use [Wh/mi] (1)**	**Battery energy [kWh] (2)**	**Retail differential price [$]**	**Cost of Electricity for 100K miles at $0.06/kWh (3)**	**Gasoline for baseline ICE [gal]**	**Break-even gasoline price ($/gal) (4)**
Compact Car	202	20.2	6,280	$1424	2941	2.62
Mid-size Car	249	24.9	6,543	$1763	3448	2.41
Full –size Car	285	28.5	6,664	$2010	4000	2.17
Small SUV	319	31.9	9,164	$2256	3846	2.97
Mid-size SUV	333	33.3	8,734	$2348	5000	2.22
Large SUV	380	38.0	9,462	$2679	5555	2.19

(1) Required battery output, average energy consumption on the FUDS and FHWAY drive cycles
(2) battery stored energy for 100 mile range
(3) Electricity use = (kWh/mi) * 1/ $\eta_{batterycharging}$; $\eta_{batterycharging} = 0.85$
(4) gallons gasoline by ICE*($/gal)$_{\text{breakeven gasoline}}$ = $\Delta_{\text{vehicle price}}$ + electricity cost for 100,000 miles

Other cost studies have shown similar or higher incremental prices associated with BEVs. Kromer and Heywood detail a baseline incremental cost of $10,200 for a BEV with 200 mile rage over a 2030 spark-ignition ICE and an optimistic incremental cost of $6,900. These incremental costs are similar but slightly lower than the cost of the battery, as the remainder of the vehicle is less expensive than the ICE vehicle [34].

3.5 Energy use and emissions

In general, the total energy use and emissions from the use of vehicles are the sum of the energy use and exhaust emissions from the vehicle and the energy use and emissions from the production and distribution of the fuel/energy used by the vehicle. These latter emissions are referred to as “upstream energy use and emissions” because they occur before the fuel is stored in the vehicle. In the case of battery-powered vehicles, there are no exhaust emissions and all the emissions for the vehicle result from the production and distribution of the electricity used to charge the battery. In this section, we will concentrate on CO_2 emissions, the primary greenhouse gas related to vehicle use.

The emissions (gCO_2/mi) for various sizes of electric vehicles is calculated for both the California and US grid mixes for electricity production and the results are shown in Table 7. In general, the CO_2 emissions for the electric vehicles are low especially using the California electricity production mix. It is of interest to compare the CO_2 emissions for the battery-powered vehicles with those for ICE vehicles. The CO_2 emissions span a wide range between the two types of vehicles and the comparison will depend on the source of electricity generation. The use of lower-carbon resources such as wind, solar, biomass and nuclear can reduce the CO_2 emissions even further compared to conventional and hybrid gasoline vehicles. Even using conventional generation sources, Table 7 shows clearly that electric vehicles are a very attractive approach to enable significant reductions in greenhouse gases in California.

Table 7 - CO_2 emissions and energy use of various types of battery-powered vehicles

Vehicle type	**Vehicle weight kg**	**Battery weight kg**	**Battery capacity kWh**	**Wh/mi from battery**	**Range (mi)**	**gCO_2/mi CA mix[1]**	**gCO_2/mi US mix[2]**	**ICEV[3] gCO_2/mi**
Cars								
Compact	1373	285	20.2	202	80	71	153	405
Mid-size	1695	380	24.9	249	80	88	189	472
Full	1949	475	28.5	285	80	100	216	540
SUV								
Small	2103	380	31.9	319	80	112	242	515
Mid-size	2243	475	33.3	333	80	117	253	667
Full	2701	570	38.0	380	80	176	380	756

Battery charging efficiency = 90%

[1] CA in state grid mix - 316 gCO_2/kWh

[2] US grid mix – 695 gCO_2/kWh

[3] baseline gasoline port fuel injected engine 2006

4. MARKET READINESS CONSIDERATIONS

4.1 Electric vehicle sales/leases and demonstration programs

As discussed in Section 1 and shown in Table 5, auto companies around the world have built a number of battery powered electric vehicles over the last fifteen years and have made them available for sale and/or lease to fleets and/or private individuals. The first set of BEVs in Table 5 are full-function electric vehicles and were developed to meet the requirements of the California ZEV Mandate. In nearly all cases, the experiences of the users of the vehicles were favorable and the vehicles operated with relatively few maintenance problems. Except for a few RAV4 electric vehicles, all the full function BEVs sold/leased as part of the ZEV Mandate have been recalled by the manufacturers. At the present, all BEVs available for sale to the public are neighborhood electric vehicles (NEV), which are the second group of vehicles shown in Table 5. Those vehicles by law in the United States are limited to a maximum speed of 25 mph and travel on roads/streets where the posted speed limit is 35 mph or less. The markets for the NEVs are limited for that reason. Some of NEVs are built on a regular small car chassis and operate much like a small car. Other NEVs are built on a golf-cart chassis and look and operate much like a golf-cart. The highest selling EV in the United States is the GEM, which is manufactured by Chrysler. All the NEVs use lead-acid batteries primarily due to cost. Most of the full function BEVs used nickel metal hydride batteries.

At the present time, the auto industry has expressed little interest in further development of full-function electric vehicles in the United States. There is, however, considerable interest in electric vehicle development in several other countries – namely, France, Japan, China, and Canada. China recently has concluded a national EV program with the testing of vehicles using lithium-ion batteries in an electric version of the Toyota Echo manufactured in China. The vehicle in China is a full function EV with a range of about 150 km. China also has a large battery development program aimed at batteries for BEVs. At the present time, there is more interest in BEVs and fuel cell powered vehicles in China than in hybrid-electric vehicles.

There is also new interest in EVs in Japan. Tokyo Electric Power Company and the Mitsubishi Motor Company have a joint program for the development of a 4-passenger electric vehicle with a 40 kW electric motor and a high voltage pack of lithium-ion batteries [31]. There are presently a few prototypes of the vehicle being tested in Tokyo and there are plans to build as many as 3000 by 2008. Fast charging the battery in 15 minutes is also being studied in connection with this project. The Japanese Government (Ministry of Economy, Trade, and Industry) has recently announced a new battery program to double the energy density of lithium batteries by 2015 to facilitate the development and introduction of electric-drive vehicles (battery powered and PHEVs) in Japan.

The EDF electric utility company in France is continuing to pursue the possibilities for electric vehicles in Europe. This work is being done in conjunction with Citroen, Peugeot, and Renault. The new electric vehicles in this program use lithium-ion and sodium-metal-chloride (Zebra) batteries and include small passenger cars and a microbus. The French program also includes testing of a fast charge system.

These recent electric vehicle and battery programs outside the United States indicate that there is a renewed interest in battery powered vehicles as a means to reduce fuel (gasoline) consumption and CO_2 emissions in those countries. The vehicle and battery products resulting from the projects cited above are likely to have a significant impact on the future of electric vehicle markets in California as the technologies are proven and true costs are better understood. They should be watched closely in the next few years.

4.2 Vehicle performance

Previous discussions of the BEVs that have been produced in the last 10-15 years for use in California indicate that designing and building EVs with excellent acceleration performance (0-60 mph times of 8-9 seconds and lower) and high speeds on all types of roads (>75 mph) is not a problem. Many such electric vehicles have been produced and operated by the general public. Electric driveline technologies continue to improve both in terms of size and efficiency. Vehicle range continues to be limited to about 300 km (~200 miles) due to both the energy density and high cost of the advanced batteries. Batteries are being developed that accept fast charge if the proper high power charging stations become available. Hence it is becoming clear that the performance of electric driveline technology will not preclude the design and marketing of electric vehicles suitable for the mass market. The required technology is approaching market readiness at the present time and further improvements will materialize as the same technologies are used in hybrid-electric vehicles whose markets are rapidly growing.

4.3 Initial vehicle cost/price

As discussed in Section 3.4, the difference in retail price between a battery-powered vehicle and a comparable ICE powered vehicle of the same type is significant, between $6000 and $9000 depending on vehicle type. This is expected to be the case when assuming high volume BEV production, using electric motor and battery costs that are projected for future mass production. Initial cost differences would be significantly higher. Furthermore, the cost calculations were done for a range of only 160 km (100 miles). Vehicle cost differences would be considerably higher for electric vehicles with significantly longer ranges of up to 300 km (~190 miles). All the vehicles considered in this cost study used lithium-ion batteries with a unit OEM cost of $250/kWh, which is well below present costs and approaching the USABC target of $150/kWh. The corresponding breakeven gasoline cost (to achieve equivalent lifecycle cost per mile) was found to be between $2-$3/gal, which is quite reasonable in the present fuel market. Further discussions of battery costs and economic hurdles for mass marketing BEVs are included in Section 4.5.

4.4 Battery availability and cycle life

The energy storage battery is the key new component in a BEV. Battery development for BEVs has been underway for about 30 years and good progress has been made. Large batteries are now available with satisfactory performance and relatively long life. In the case of nickel metal hydride batteries, both laboratory and in-vehicle testing has shown good cycle life in excess of 2000 deep discharge cycles. Similar test data are not yet available for lithium-ion batteries, but it is expected that a cycle life of at least 1000 cycles will be achieved with presently available technologies. While large batteries suitable for use in BEVs are available, they are not yet mass produced like is the case for the small cell batteries used in consumer electronics. If it becomes clear to the battery industry that the market for large lithium batteries for vehicles is likely to develop, it can be expected that facilities to mass produce the large batteries will be developed and built. An alternative BEV design, shown in the Tesla motors EV uses thousands of laptop computer batteries in their vehicle instead of larger EV batteries to take advantage of their existing level of mass production and currently lower costs.

4.5 Technical and economic hurdles

As indicated previously in Section 4.3, there remains a large hurdle relative to the cost of large batteries for BEVs. The vehicle cost calculations shown in Section 3.4 indicate that even for an OEM battery unit cost of $250/kWh, the retail price of the electric vehicle will be $6000-$9000 higher than the comparable baseline ICE vehicle, for a battery vehicle with a 100 mile range. The USABC cost targets for EV batteries are $150/kWh in the near term and less than $100/kWh in the long term. If these are taken to be the OEM costs, the corresponding retail cost is still significantly higher by a factor of about 1.4 resulting in a contribution to the retail price of the

EV being $140 -$210/kWh of energy stored in the battery. The energy stored in the battery for a specified range can be reduced by reducing the vehicle weight and road load (coefficient of drag, frontal area and rolling resistance), but this will likely add to the cost of the vehicle. Discussions with battery manufacturers indicate they are not optimistic that battery costs can be lowered to meet the USABC cost goals [33] and auto manufacturers are not optimistic that large reductions in the vehicle weight and aerodynamic drag can be made at reasonable cost while still maintaining vehicle utility and crash safety. This is especially true if vehicle ranges significantly greater than 100 miles are needed to mass market BEVs.

Hence it appears that a non-technical strategy is likely to be needed to make electric vehicles attractive to consumers at what are presently thought to be reasonable prices for gasoline. These strategies should focus on ways to redirect the consumer's primary consideration from the high initial vehicle cost to life-cycle or effective operating cost including the cost/mile of the battery and cost of recharging it. The breakeven cost calculations in this study as well as those in [22] indicate that when considered in terms of effective lifecycle costs, electric vehicles can become economically attractive to many potential vehicle buyers. In addition, buyers could also be attracted by the public benefits of these vehicles: they are zero-emission vehicles, enhance energy security and reduce petroleum dependence, reduce greenhouse gas emissions, and have the potential to use renewable energy sources.

4.6 Market synergies with electric-drive vehicles

BEVs are part of a larger class of electric drive vehicles, those that use electricity as some or all of their propulsive energy. These vehicles use all share common components including batteries, electric motors, power electronics and controller systems. Examples of other electric drive vehicles include internal combustion engine hybrid electric vehicles such as the Toyota Prius, plug-in hybrid electric vehicles, and fuel cell vehicles. Because of their shared components, development of any of the other vehicle types has benefits to the entire class of electric drive vehicles, helping to expose consumers to new technologies, bringing experience, cost reductions into the research and development, vehicle design and manufacturing processes. Battery electric vehicles are not likely to be mass-market consumer vehicle in the near term, but development on batteries for HEVs and PHEVs will help to bring down component costs and improve the prospects for BEVs in the long term.

In some localities, there have been significant sales of neighborhood electric vehicles (NEVs). These vehicles in the United States are limited to speed of 25 mph and can only be driven on roads with low speed limits. The NEVs are clearly niche vehicles that are not suitable for mass marketing as a replacement of conventional ICE vehicles. The city electric vehicle (CEV) is another option that could have a top speed of about 50 mph and be safe to drive on all city streets regardless of the speed limit. In most cases, these BEVs would be small cars with adequate, but modest, acceleration performance with a range of 50-75 miles. As indicated in
Table 5, CEVs have been built in the past by several auto companies, but for the most part, work on this type of vehicle has been stopped. The market for CEVs is limited, but not nearly as small as for NEVs. As indicated in
Table 5, the battery packs for CEVs would store 8-10 kWh. This is about the same size (kWh) as needed in larger plug-in hybrid vehicles (PHEV). If PHEVs are sold in large volume, this could make available at reasonable cost, batteries for CEVs. This could result in CEV prices that would lead to their commercialization in the next 5-10 years. It is possible that a gradual

evolution of a CEV market to larger and larger vehicles could result in commercialization of full-function BEVs like the GM EV1, Honda EV Plus, and Nissan Altra (**see** Table 5).

5. CONCLUSIONS

Based on the discussions in previous sections, the prospects for a significant penetration of electric vehicles into light-duty automotive markets do not appear to be promising as long as the focus of the consumers is primarily on the initial price of the vehicle and are concerned with the range limitations relative to conventional vehicles. The difficulty is not that electric vehicles would not meet the needs of many car buyers most of the time, but rather it is that the consumer is likely to have and want a less costly and more flexible means of meeting their perceived transportation needs. Vehicle range and refueling time limit the utility of electric vehicles and consumers seem to want a vehicle that meets their most demanding requirement even if it is encountered very infrequently. The higher initial price of the BEV and its reduced utility have made it difficult to sell electric vehicles except to a small subset of consumers, such as those that are environmentally conscious. However, it is likely that other advanced technology clean vehicles will be marketed in order to capture this market and full BEVs will remain a small niche.

In summary, the significant market penetration of battery powered electric vehicles is not likely to occur in the near future except for very specialized applications of NEVs in special communities that are configured with special roads or lanes for them. Some of the attractive features and advantages of electric vehicles will become apparent to the public if/when PHEVs are introduced in reasonably large numbers in the relatively near term. This could lead first to city electric vehicles (CEVs) and then ultimately to larger BEVs in the longer term.

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