Issues in Energy Storage for Electric-Based Transportation

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Abstract

The key to market success for electric vehicles (EVs) has always been the energy-storage device, which limits driving range and vehicle acceleration. In many respects, rechargeable lithium batteries are the most attractive technology for storing energy and delivering it on demand in an automobile. Past and ongoing efforts to develop electric-based automotive propulsion systems are chronicled in this article.

Keywords: *automotive applications, electrical properties, energy-storage materials, rechargeable lithium batteries, transportation.*

Introduction

Over the past 20 years, there has been considerable research and development devoted to electric-based transportation systems.[1–8] Historically, this effort was driven in large part by the desire to improve urban air quality, but more recently, it has been seen as having the potential to reduce the need for imported petroleum for those countries who rely on it. Electric-based transportation offers the unique prospect of improving the environment while conserving fossil fuels for nonpolluting applications.[9–11] Advances in the performance of electrochemical power sources have brightened the prospects for electric vehicles (EVs).[9,12,13] Some have even gone so far as to predict that combustionless technologies will dominate and eventually replace the internal-combustion engine (ICE) in the next few decades.[9,10]

In parallel with advances in batteries, there has been tremendous progress in the development of the EV and its components,[14,15] including electronic control and power-management systems.[16,17] Recent experiences of several auto manufacturers indicate that shortcomings in battery performance translate into major obstacles to the broad acceptance of the EV by the motoring public. Ironically, aside from the power-source limitations, EVs have been developed that in many respects outperform their ICE-powered counterparts.

Although past predictions for batteries in automotive applications have had a tendency to be overoptimistic, recent performance data obtained from advanced batteries provide a more realistic forecast.[18–20] Large-size batteries with high energy and power capabilities have been built and tested for EVs and hybrid electric vehicles (HEVs), and the results confirm the prospects of the technology for transportation applications.[13,21–25] In addition, safety aspects of EV and HEV batteries have been improved considerably, and many internal (chemical) and external (electronic) controls have been developed to provide an extra margin of protection.[26–39] Furthermore, there are opportunities for reducing the cost of advanced batteries through smart engineering of functional and low-cost materials.[40]

Although the capital cost of an EV is higher than that of its ICE-powered counterpart, there are benefits to EV ownership, some of them at the societal level: for example, an expected decrease in the cost of health care due to reduction in urban pollution, a decrease in noise pollution, and a reduction in corrosion and other chemical degradation of the transportation infrastructure from the chemical effects of conventional vehicle emissions. These effects are difficult to quantify, however, and so far remain unreported in a systematic way.

In recognition of the benefits of EVs, there are coordinated efforts nationally and internationally to develop a practical product. Many organizations have contributed to the development of electric-based transportation, for example, the U.S. Advanced Battery Consortium (USABC), Freedom CAR, Partnership for a New Generation of Vehicles (PNGV), and the U.S. Department of Energy (DOE) through its Office of Advanced Automotive Technologies (OAAT), which supports Batteries for Advanced Transportation Technologies (BATT). Other related U.S. government programs include those under the military research agencies: the Department of Defense (DOD), the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), and the Office of Naval Research (ONR). Similar activities exist in Europe and Japan, where coordinated efforts are under way among industry, government agencies, and national laboratories to enhance the development of electric-based transportation.[5,41]

Battery technology is critical not only to the successful development of a practical EV, but also for other modes of electric-based transportation, including fuel-cell-powered vehicles.

Hybrid Electric Vehicles

There have been many proposals to combine two or more power sources in order to satisfy both the energy and the power requirements of EVs. Such multi-powered vehicles are commonly known as hybrid electric vehicles (HEVs). Many combinations of power sources have been proposed for HEVs, including battery/small ICE, fuel cell/turbo generator,[42] supercapacitor/battery, supercapacitor/ICE, battery/fuel cell, supercapacitor/fuel cell, fuel cell/ICE, and high-power battery/high-energy battery.[43,44] Figure 1

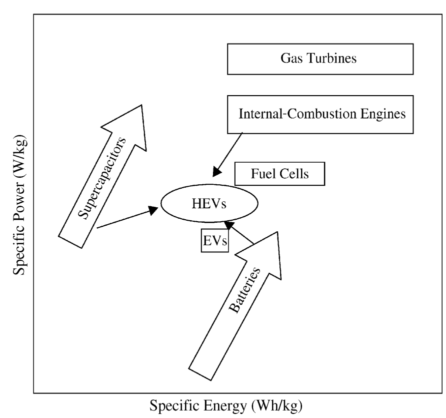

Figure 1. Ragone plot showing the relative merits of various power-source technologies for electric vehicles (EVs) and hybrid electric vehicles (HEVs).

shows the relative merits of various technologies on a Ragone plot.

How such combinations attempt to meet the energy and power requirements of a vehicle is illustrated by the power systems that use a supercapacitor, which provides high-pulse power for start-up, hill-climbing, and acceleration, while the battery, fuel cell, or ICE provides energy for the desired driving range. These combinations can be designed to work in a dual mode in which the drive train is powered either from the energy-storage device or from the ICE, in power-assist mode where the energy-storage device and gasoline engine can be utilized simultaneously, or in a mode in which two power sources perform at their optima. By way of example of this last mode, supercapacitors are used for their unique power-delivery capability, and batteries or fuel cells provide steady-state power at low to moderate rates. Most hybrid vehicles on the market today are based on the combination of a battery and a small ICE. The choices of battery chemistry have included lead-acid, nickel-metal hydride, and lithium-ion.

Although the hybrid system benefits from the optimized performance of multiple power units, in the interest of reducing complexity and therefore improving reliability, the ideal scenario is to have only one power source, for example, a battery capable of delivering both the required power and energy.

Motor and Controller

To derive maximum benefit from the electric power source, major efforts have been directed at improving the motor–controller system to reduce weight and improve energy utilization.[45,46] Electronic controls operating with a smart neuronetwork and fuzzy logic can update the status of the power requirements and power-source condition (i.e., battery voltage, state of charge, resistance, temperature, pressure, etc.) every few seconds in order to anticipate future power demand and regulate the power management through the entire EV system. Computer programs enable power-flow analysis and state-of-charge recognition as well as energy recovery during regenerative braking. The power management and data analyses usually include a microprocessor-based programmable logic controller, a computer for data acquisition, and a communication bus. The EV can use a permanent magnet synchronous motor, which is more efficient than either a dc or ac motor. High-magnetic-density Nd-Fe-B magnets provide high-output-to-weight-ratio rotors with extended durability and heat resistance. The motor also works as a generator during braking and transforms kinetic energy into electrical energy that can be stored in the battery.

Advanced Rechargeable Lithium Batteries

Advanced rechargeable lithium batteries are the most promising energy-storage devices for EVs and HEVs.[47] With prospective energy densities of 400 Wh/kg and power densities of 800 W/kg, such rechargeable batteries have, in principle, the capability of satisfying all of the performance requirements of an EV.[48] Table I shows the criteria established over a decade ago by the USABC for advanced battery technologies. To this day, there is no commercially available battery that comes close to satisfying them. Materials limitations to advanced rechargeable Li batteries exist, however. The most crucial element in need of improvement is the cathode (see the articles by Sides et al. and by Delmas and Croguennec in this issue)—specifically, greater capacity combined with higher rate capability at an acceptable cost for the automotive market.

Fuel Cells

Since the mid-1990s, there has been a dramatic increase in the attention given to the development of fuel cells as a source of electric power for automotive traction.[49,50]

Table I: U.S. Advanced Battery Consortium (USABC) Primary Criteria for Advanced Battery Technologies.

Power density (W/l)	600
Specific power, discharge (W/kg, 80% DOD[a]/30 s)	400
Specific power, regeneration (W/kg, 20% DOD/10 s)	200
Energy density (Wh/l, C/3[b] discharge rate)	300
Specific energy (Wh/kg, C/3 discharge rate)	200
Life (years)	10
Cycle life (cycles, 80% DOD)	1000
Power and capacity degradation (% of rated spec.)	20%
Ultimate price ($/kWh, 10,000 units @ 40 kWh)	$<$100
Operating environment	-40 to 85°C
Normal recharge time	3–6 h
Fast recharge time	40–80% SOC[c] in $<$15 min
Continuous discharge in 1 h (no failure)	75% (of rated energy capacity)
Efficiency (C/3 discharge; 6-h charge)	80%
Self-discharge	$<$15% per month
Maintenance	No maintenance (service by qualified personnel only)
Abuse resistance	Tolerant (minimized by on-board controls)
Other criteria	Recyclability, 100% Packaging constraints Environmental compliance (manufacturing process, transport, in use, and recycling) Reliability (tie to warranty and cycle life) Safety constraints Vibration tolerance

Note: From Reference 54.
[a] DOD is depth of discharge.
[b] A discharge rate of C/3 means that the time for total discharge of the battery at constant current is 3 h.
[c] SOC is state of charge.

Although fuel cells of various types—alkaline, molten carbonate, solid oxide, phosphoric acid, and proton-exchange membrane (PEM)—have been investigated, it is the hydrogen–oxygen PEM fuel cell that is emerging as the primary chemistry for this application. In the hydrogen–oxygen fuel cell, hydrogen is used as the active anode material, and oxygen from air is used as the active cathode material. The overall reaction is the formation of water vapor. The hydrogen is supplied from a storage tank or from a reforming unit that generates hydrogen from H-containing fuels such as gasoline, natural gas, or methanol. The oxygen is supplied from humidified air. The electrochemical reactions are

$$\text{on the anode: } H_2 \rightarrow 2H^+ + 2e^- \ (-); \quad (1)$$

on the cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O\ (+); \quad (2)$$

$$\text{overall reaction: } H_2 + \frac{1}{2}O_2 \rightarrow H_2O. \quad (3)$$

The anodic reaction is "fueled" by hydrogen; the oxygen for the cathodic reaction is taken from ambient air. While these reactions appear straightforward, there are formidable obstacles that must be overcome before PEM-based fuel cells can be considered viable for powering automobiles. Among these are the generation and storage of ultrahigh-purity (99.9999%) hydrogen, which requires catalysts capable of converting cheap hydrocarbon feedstock to hydrogen containing extremely low levels of carbon monoxide, in order to avoid poisoning the precious-metal electrodes of the fuel cell.[50] Storage of hydrogen in a manageable volume for transportation requires breakthroughs in hydrogen-storage materials (a topic that will be covered in the September 2002 issue of *MRS Bulletin*). Solid-state hydrogen storage in transition-metal alloys is not practical because of their low gravimetric capacity.

The assembly of fuel-cell electrodes into stacks that deliver adequate power for automotive traction is another challenge. The cathodes are susceptible to poisoning by airborne emissions from vehicles burning leaded gasoline. While progress has been made with fuel-cell membranes, conductive electrode substrates, low catalyst loading, stack engineering, and hydrogen-storage materials, cost and reliability remain impediments to the widespread adoption of fuel-cell power for automobile propulsion.[51] Finally, there is the thornier issue of infrastructure to support the supply of hydrogen.

Redox-Flow and Other Batteries

Redox-flow batteries also have been proposed for EV applications.[52] The vanadium redox system containing vanadium sulfate and dilute sulfuric acid can be pumped and recharged at a service station on the same time scale as pumping gasoline into conventional vehicles. The problem with this system is the low concentration of vanadium salt and, therefore, the large size of the fuel tank. Increasing the solubility of vanadium salt by chelating agents is under investigation. The application of redox-flow batteries for load-leveling and peak-power-shaving is also under consideration. Metal–air battery technology is also under development, particularly the Zn–air and Al–air systems.[53] Metal powders are the fuel for these batteries; at the end of each cycle, the electrolyte must be flushed and the dissolved metal in the electrolyte reduced to elemental metal, which is subsequently recharged as fresh anode-active material. As with the PEM fuel cell, regardless of the performance metrics of the technology, the infrastructure question remains a serious impediment to adoption.

Concluding Remarks

An all-electric vehicle with satisfactory driving range (300 miles per charge) and fast charging capability is arguably the most attractive solution to the environmental problems associated with automobile use. Depending upon the long-range developments in our mix of electric-power generation, the widespread use of EVs can have a beneficial effect on national energy security. However, no single commercially available battery technology can yet satisfy the energy and power requirements of EVs. This situation is rapidly changing, however. The main challenge remains the cathode. There has been significant progress in hybrid vehicles, particularly battery/internal-combustion-engine systems. As battery technology improves, the size and utilization of the internal-combustion engine will be reduced toward the ultimate goal of all-electric propulsion. Proton-exchange membrane fuel-cell technology awaits breakthroughs in a membrane–electrode assembly capable of operating at higher temperatures with (1) lower catalyst loading; (2) highly conductive, corrosion-resistant bipolar plates; (3) stack engineering including water and thermal management; and (4) a practical and safe on-board hydrogen-storage system. Even so, proper utilization of fuel-cell power for automotive traction, including start-up, peak-power-shaving, and storage of regenerative braking energy, will likely require assistance from advanced batteries.

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