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Energy on Demand

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The increasing demand and subsequent increasing price of fossil fuels have coupled with concern over global warming to encourage interest in sustainable forms of energy and "greener" transportation. Hybrid vehicles are slowly gaining ground on traditional vehicles, bringing improved fuel efficiency and greater consumer interest in electric vehicles. The availability of mass-produced electric vehicles, however, has remained elusive. Better batteries – or other methods of energy storage appropriate for use in transportation applications – are seen as key technologies for the continued advancement of hybrid and all-electric vehicles. Although simple batteries have been in existence for 200 years, energy storage has never been more at the forefront of vehicle design than it is today.

Industry, government, and academia are collaborating in an effort to identify and overcome the technological hurdles of energy storage in transportation applications. In the United States, the FreedomCAR and Vehicle Technologies program and the U.S. Advanced Battery Consortium (USABC) developed ambitious targets for energy storage technology for use in electric vehicles (EVs) and hybrid electric vehicles (HEVs) (Table 1) [1]. Additional USABC targets are summarized in the article by Duong et al. in this issue. Performance indicators for three leading battery chemistries – lead-acid, nickel-metal hydride (NiMH), and lithium-ion (Li-ion) – are also presented elsewhere in this issue (see article by Van Mulders et al.).

Upon comparing these USABC targets and current performance indicators, it becomes apparent that the development of all-electric vehicles is limited by the low specific energy and high cost of commercially available batteries. These barriers are not new; indeed they have been the focus of electric vehicle battery research for over 30 years [2]. Yet, with specific energies of up to 140 Wh/kg [3, 4], even Li-ion battery systems fall far below the specific energy benchmark set by gasoline (12,722 Wh/kg) [5]. The low specific energies of current battery systems effectively limit the range of all-electric vehicles and therefore encourage the development of hybrids. Hybrid vehicles utilize the high specific energy of liquid fuels in the relatively inefficient internal combustion engine to extend the limited driving range afforded by the relatively low specific energy (but highly efficient) battery systems. Thus, a trade-off between driving range and energy efficiency is established.

Examination of the USABC goals demonstrates that there are market niches for a variety of battery capabilities depending on the level of hybridization demanded – i.e., the "purpose" of the battery. Lead-acid batteries, the oldest of the three technologies, have sufficient specific energy and power for mild hybridization and less demanding all-electric applications and a significant cost advantage over other chemistries. Moving towards greater levels of hybridization and/or more demanding applications generally requires the greater specific energy and specific power of the NiMH and Li-ion chemistries. Indeed, NiMH and Li-ion batteries can achieve the USABC targets for specific power under laboratory conditions [6, 7]. These chemistries, however, involve significantly higher costs [5]; thus, demonstrating increased fuel efficiency, decreased emissions, or other desirable properties is necessary to justify the notably higher price tag.

Calendar life and cycle life are also critical issues, as these areas involve quality of performance, durability, market acceptance, and manufacturer warranty liability. Cycle life is strongly affected by the level of discharge the battery experiences between chargings. The usable state of charge directly governs the amount of energy that is available between chargings. The ability of the battery to withstand the level of discharge routinely expected in a given application is critical. Lead acid batteries, for instance, have shortened cycle life with routine shallow discharges [8], inhibiting more extensive use in HEVs.

Additionally, other issues revolve around information that is only partially represented in the selected data above. The target for temperature operating range is also a barrier in that many battery systems perform best in a fairly narrow range of temperatures (e.g., 25°C - 35°C), and changes in temperature can drastically impact battery performance and cycle life. Controlling battery temperature during operation can also be critical for maintaining safety standards and preventing thermal runaway, particularly for lithium-based chemistries. As specific energy increases, so

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	Power-assist HEV Battery (Minimums)	Plug-in HEV Battery (40 mi range, EV mode)	EV Battery	Ultracapacitors (42V Power Assist)
Specific Energy (Wh/kg)	7.5	97	150	3
Specific Power - discharge (W/kg)	625 (10 sec)	317 (10 sec)	300 (30 sec)	650 (2 sec)
Temperature Operating Range (°C)	-30 to +52	-30 to +52	-40 to +50	-30 to +52
Cycle life	300,000	300,000	1,000	750,000
Calendar life (yr)	15	15	10	15
Specific cost ($/kWh)	1667	293	150	2167

Table 1: FreedomCAR and USABC energy storage goals

does the possibility for safety issues and the necessity of designing for abuse tolerance [9]. Hence, it is critical that the battery system monitor performance and relevant operating conditions such as temperature and respond appropriately to prevent damage to the vehicle or user.

Although they typically receive less attention than batteries as energy storage solutions, ultracapacitors are also prime targets for continued development. Ultracapacitors have higher power and lower energy density than batteries and are well-suited for mild hybridization and high power vehicle applications. Commercially available ultracapacitors currently have specific energies ranging from 1.1 – 8 Wh/kg [8, 10] as compared to the USABC target of 3 Wh/kg and specific powers ranging from 800-1400 W/kg as compared to the target of 650 W/kg for use in power-assist hybridization. A key issue currently prohibiting more extensive use of ultracapacitors in hybrid applications is cost. Currently, acquisition cost [11] is an order of magnitude higher than the USABC goal. The extended cycle life of ultracapacitors, however, may in some applications more than compensate for the higher cost.

The articles contained in this issue highlight current research efforts in battery and ultracapacitor technology. Battery system design is emphasized, including methods of controlling temperature and monitoring performance. Novel approaches to sizing batteries to minimize fuel consumption and greenhouse gas emissions in HEVs are discussed. A new permanent magnet propulsion system demonstrating higher power for high performance EVs is also presented. Extensive use of simulations demonstrates how energy storage solutions can be designed to meet the needs of a specific market segment, thereby providing additional direction for imminent vehicle deployments as well as long-term research.

The ability to store and provide energy as demanded by the driver is indeed a key technology for the development of fuel-efficient, environmentally friendly transportation. A number of hurdles – calendar life, operating temperatures, abuse tolerance, production cost – have yet to be perfectly met by any one technology. Current commercial vehicles clearly demonstrate, however, that utilizing additional energy storage maximizes the abilities of the HEV's engine and paves the road to cleaner and more efficient transportation technologies of the future.

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